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**SPECTRAL ANALYSES OF HIGH-FREQUENCY PN/SN PHASES FROM VERY SHAL--ETC (U)**

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→ refracted P from earthquakes and explosions. From 12 August 1981 through 15 October 1981, the Wake hydrophones served as key elements within an approximate 1500 km line of ocean bottom seismographs and hydrophones (OBS's) aimed towards the southern Kuriles. Twelve OBS's were spaced at intervals of about 135 km. Ninety-nine located events were recorded. Again many of the phases were high-frequency Pn/Sn, and some were mantle-refracted P from earthquakes and explosions.

→ A major software advancement was the development of a program that would determine the mean composite spectrum and standard deviations from a number of individual spectrums. The program has been used in a search for the normal-mantle refracted P phase within the Pn coda at distances less than about 21° (2335 km) and has been used to obtain composite spectrums for ocean bottom noise and for nuclear explosions and earthquakes at great distances.

→ No evidence was found for the normal, mantle-refracted P phases at their predicted arrival times within the Pn codas of events at distances of less than 21°, further emphasizing the importance of high-frequency Pn phases in monitoring earthquakes or explosions in an oceanic environment.

→ The levels of noise on the deep ocean bottom were found to be comparable to those found at the quietest continental sites. This fact and the obvious advantages of the thinner oceanic crust (less attenuation and distortion) suggest a potential for large signal/noise ratios on the deep ocean bottom. This potential has been confirmed by actual observations of the Wake Island hydrophone array.

→ Explosions were found to have less energy at frequencies below 1.5 Hz and more energy at frequencies above 2 Hz than shallow focus earthquakes of comparable epicentral distance and magnitude.



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- I. "Spectral Characteristics of High-Frequency Pn, Sn Phases in the Western Pacific" by D. A. Walker, C. S. McCreery, and G. H. Sutton.
- II. "A Description of Programs for Computing Individual and Composite Calibrated Spectra of Discrete Time Series with Variable Duration" by C. S. McCreery.
- III. "Spectra of Nuclear Explosions, Earthquakes, and Noise from Wake Island Bottom Hydrophones" by C. S. McCreery, D. A. Walker, and G. H. Sutton.

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MATTHEW J. KERPER  
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## RESEARCH OBJECTIVES

During the past year (3 March 1981 through 2 March 1982), our primary research objectives under the original contract were to have been as follows.

- A. Improve the Wake Island hydrophone system to record small underground nuclear explosions. These improvements should include quieter pre-amplifiers, filtering and gain setting modifications, repair non-operating channels, eliminate cross talk between channels, and an improved speed controlled drive motor for tape recorders.
- B. Investigate the high-frequency Pn/Sn Phases recorded from near surface circum-Pacific earthquakes and relate the spectra of these phases to focal depth, source functions and path parameters.
- C. Develop discriminate techniques using the characteristics of high frequency, normal, mantle-refracted P phases from underground nuclear explosions.

## PROGRESS

### A. Improvements in the Wake System

The largest typhoon in more than twenty years struck Wake Island in March of 1981. Unfortunately, the hydrophone recording instrumentation was located within a few feet of the floor and the resulting extensive flooding of the island extended into the building and destroyed the instruments. Thus, the planned improvements became, in fact, a total reconstruction of the recording system. [Fortunately, no noticeable damage was done to the hydrophones or their cables.]

Aside from the financial hardships posed by this disaster, the timing threatened to jeopardize our ONR sponsored ocean bottom seismograph (OBS) experiment in the Western Pacific (to be discussed later in this report), since the Wake system was to have served as a critical element of a 1500 km

line of OBS's aimed towards the southern Kuriles from mid-August through mid-October of 1981.

With outstanding help from our engineering support facility group, the Wake system was, nonetheless, reactivated in July. Many of the problems associated with the old system were either eliminated or substantially reduced. Improvements included quieter amplifiers, greater fidelity produced by improved speed control on the tape drive motors, and an increased dynamic range. Also, the instrument was mounted on the wall, well above floor level, in a sealed cabinet. Since reactivation, numerous seismic phases have been recorded, with many being high-frequency Pn/Sn and some being normal, mantle-refracted P from earthquakes and explosions.

#### B. Studies of Pn/Sn Spectra

The task of relating Pn/Sn spectra to focal depth, source functions, and path parameters has proven to be the most elusive of our three major objectives. The most logical approach to this task presupposed an understanding of the mechanism for the generation and propagation of these unusual phases. Since such an understanding does not yet exist, our efforts have been focused primarily on the achievement of that understanding. More specifically, we have attempted to accurately quantify the observational characteristics of these phases (primarily velocity and frequency content, and changes in these parameters as a function of distance), and to promote interest and research on the phenomenon through our publications.

To accurately quantify the observational characteristics of high-frequency Pn/Sn phases, the Office of Naval Research supported the deployment of 12 OBS's in an approximate 1500 km line aimed towards the southern Kuriles and passing through the AFOSR supported Wake hydrophone array. During

the sixty-five days of recording, ninety-nine located events were recorded. Again, many of the phases were high-frequency Pn/Sn, and some were mantle-refracted P from earthquakes and explosions. The Wake hydrophone array functioned perfectly during the experiment, providing an additional station which in many instances proved to be of critical importance. Preliminary analyses indicate that the major objectives of the OBS experiment were achieved, thereby increasing prospects for understanding the mechanism of Pn/Sn propagation. Evaluation of this data (jointly sponsored by ONR and AFOSR) will continue through the summer with publication planned for the fall of 1982.

Another attempt to quantify the observational characteristics of Pn/Sn is offered in the report entitled "Spectral Characteristics of High-Frequency Pn/Sn Phases in the Western Pacific" which has been submitted to the Journal of Geophysical Research for publication and is appended to this report. An aspect of this study which may be of special interest to AFOSR concerns a search for the normal, mantle-refracted P phase within the Pn coda at distances less than about  $21^\circ$ . At these distances Pn arrives ahead of the expected arrival time of P. Presumably P is within the Pn coda, and the difficulty in observing this phase on analogue recordings is due to significant amounts of energy in Pn at the dominant frequency of P (i.e., 1 to 2 Hz). Detailed spectral analyses of Pn codas, however, do not substantiate this presumption. In other words, no evidence can be found for normal, mantle-refracted P phases within the Pn codas of events at distances of less than  $21^\circ$ . This finding further underscores the importance of high-frequency Pn phases in monitoring earthquakes or explosions in an oceanic environment.



Mention should also be made of a special software program developed during the past year. This program determines the mean composite spectrum and standard deviations from any number of individual spectrums. It has been used in the above mentioned paper ("Spectral Characteristics...") and in a paper which will be discussed later in this report. Such a program will also be essential in relating variations in spectra to focal depths, source functions, and path parameters. A detailed description of this program is given in the appendices.

#### C. Discrimination

Regarding the task of discriminating the spectra of mantle-refracted P phases for explosions and earthquakes at great distances, efforts during the past year have been successful. Explosions were found to have less energy at frequencies below 1.5 Hz and more energy at frequencies above 2 Hz. Earthquakes were found to have a spectral slope of -28 db/octave (relative to pressure) over the band of 1-6 Hz. Explosions were found to have the same spectral slope over the band 2.2-6 Hz. [Refer to Figure 2 of the paper "Spectra of Nuclear Explosions, Earthquakes, and Noise from Wake Island Bottom Hydrophones" appended to this report.]

Another important finding presented in the above mentioned paper is the low level of noise at high frequencies on the ocean bottom. Levels were found to be comparable to those found at the quietest continental sites. This fact and the obvious advantages of the thinner oceanic crust (less attenuation and distortion) suggest a potential for large signal/noise ratios on the deep ocean bottom. This suggestion has been confirmed and is demonstrated in Figure 3 of the "Spectra of Nuclear Explosions..." paper.

APPENDIX I

Spectral Characteristics of High-Frequency Pn,Sn  
Phases in the Western Pacific

by

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(Submitted to JGR in May 1982)

Abstract. Pn and Sn phases from twenty-five selected earthquakes recorded since July of 1979 on ocean bottom hydrophones near Wake Island are used to complement and extend prior investigations of high-frequency Pn, Sn spectra in the Western Pacific. At a distance of about  $18^\circ$  ( $\approx 2000$  km), frequencies for Pn and Sn are as high as 30 and 35 Hz, respectively; at a distance of about  $30^\circ$  ( $\approx 3300$  km), as high as 15 and 20 Hz, respectively. Pn phases lose their high-frequency energy more rapidly than Sn phases do, yet Pn wavetrains are much longer than Sn wavetrains. Pn wavetrains of longer duration, more energy, and higher frequencies are found for travel paths primarily in the Northwestern Pacific Basin than for travel paths across the transition zone from the shallow Ontong-Java Plateau to the deep Northwestern Pacific Basin. Sn phases are extremely weak or absent for travel paths crossing this transition zone from the shallower Ontong-Java Plateau to the deeper Northwestern Pacific Basin, whereas Sn phases are well recorded for travel paths crossing the transition zone in the opposite direction. Although normal, mantle-refracted P phases are well recorded beyond about  $21^\circ$  ( $\approx 2300$  km), available data indicate that normal, mantle-refracted P phases may not exist at distances less than  $21^\circ$ .

### Introduction

Recent investigations of high-frequency Pn, Sn in the Pacific [Walker, 1977; Walker et al., 1978; Sutton et al., 1978; Talandier and Bouchon, 1979; and McCreery, 1981] suggest that the real character of these phases is revealed at frequencies much higher than those traditionally associated with normal, mantle-refracted body waves at teleseismic distances (i.e.,  $\approx 1$  Hz). For example, in one investigation [Walker et al., 1978], frequencies as high

as 12 and 15 Hz were found for the Pn and Sn phases, respectively, of an earthquake recorded at a distance of  $28.3^\circ$  (3147 km).

In this report we offer a more comprehensive analysis of the spectral characteristics of Pn,Sn using additional data recorded since July of 1979 on ocean bottom hydrophones near Wake Island. Only undistorted arrivals with signal/noise ratios of at least 3/1 were used in this investigation. Epicentral distances, origin times, depths, and magnitudes are given in Table 1; and locations of epicenters are shown in Figure 1.

#### Northwestern Pacific Basin Travel Paths

Spectrograms for some of the Pn,Sn phases having travel paths primarily under the deep Northwestern Pacific Basin (i.e., events 1 through 18) are shown in Figure 2. All reveal high frequencies, with values in excess of 20 Hz for both Pn and Sn at a distance of  $18.0^\circ$  (2002 km; event no. 2) and values of up to 15 and 20 Hz for Pn and Sn, respectively, at a distance of  $29.4^\circ$  (3269 km; event no. 17). (More detailed spectral analyses of the phases for event no. 2 at  $18.0^\circ$  indicate values as high as 30 and 35 Hz for Pn and Sn, respectively.)

Spectrograms for event nos. 17 and 18 show the normal, mantle-refracted P phases as well as high-frequency Pn and Sn phases. Other events for which normal, mantle-refracted P phases have been clearly recorded are nos. 11, 12, 13, 15, and 16. The fact that all of these events are at distances in excess of  $21^\circ$  is not coincidental, for it is only at these distances (the precise crossover depending, in part, on focal depth) where P phases begin to arrive ahead of the high-frequency Pn phase (Figure 3). With increasingly shorter distances, high-frequency Pn arrives increasingly ahead of the expected P.

Although it might seem reasonable to assume that P does arrive at distances less than about  $21^\circ$ , but is masked by Pn, such an assumption should be tested. One test is to compare spectra where all of the P's energy, or large portions of it, might be suspected of being present within the Pn coda (i.e., event nos. 1 through 10) to the spectra where only Pn is known to exist (i.e., event nos. 13 through 18; nos. 11 and 12 could not be used due to Pn clipping). Composite spectrums have been made for the two groups of arrivals (i.e., Pn with P suspected, at distances from about  $17^\circ$  to  $22^\circ$ ; and Pn with P known to be absent, at distances from about  $26^\circ$  to  $33^\circ$ ), as well as for all P phases, at distances from about  $22^\circ$  to  $33^\circ$ , either clearly arriving well ahead of Pn (event nos. 11, 12, 13, 15, 16, 17, and 18) or suspected of arriving close to, but ahead of, Pn (event nos. 9 and 10). These composites and the individual absolute spectrums from which they were derived are shown in Figure 4. Values for individual spectrums were plotted only if they were at least 4 db above background noise. The composite curves are simply the averages for the individual curves, with the condition that no composite values were used for those frequencies at which more than one of the individual curves were not plotted.

Individual and composite P spectrums are obviously, and not unexpectedly, very different in character from individual and composite Pn spectrums, in that the P has larger signal-to-noise ratios at lower frequencies (i.e., 1-2 Hz) than either Pn (Figures 4 and 5), and the composite P is richer in lows, and weaker in highs, relative to the  $26^\circ$  to  $33^\circ$  Pn composite (Figure 5a). In comparing the composite  $17^\circ$  to  $22^\circ$  Pn spectrum to the composite  $26^\circ$  to  $33^\circ$  Pn spectrum (Figure 5b), we note that the  $17^\circ$  to  $22^\circ$  Pn is similar in character to the  $26^\circ$  to  $33^\circ$  Pn for frequencies higher than 2 Hz, but has lower signal-to-noise ratios at frequencies less than 2 Hz (i.e., values fall

below the "4 db above noise" requirement for plotting). This latter observation is also apparent for comparisons of individual spectrums (Figure 4). From this analysis, then, it does not appear that detectable normal, mantle-refracted P phases exist in the Pn codas of events at distances of  $17^{\circ}$  to  $22^{\circ}$ .

Another important, though not surprising, observation to be made from the composite plots (Figure 5b) is that Pn phases at great distances appear to be weaker at higher frequencies ( $> 10$  Hz) than Pn phases at shorter distances.

Sn composite plots have also been made for the same events for which Pn composites have been made. These plots are shown in Figure 6. Although normal mantle-refracted P phases have been well recorded at great distances, normal mantle-refracted S phases from earthquakes have not been recorded by the Wake hydrophones. Presumably this is due to the combined factors of the hydrophones responding primarily to vertical motions, and the lack of such motions in S phases at teleseismic distances. In addition, background noise levels are high for those frequencies at which S would appear.

In comparisons of the Sn composite plots to one another (Figure 6a) and to the composite Pn plots (Figure 6b and 6c), it appears that Sn phases do not lose their high frequencies as rapidly as Pn phases. Also, for both distance ranges (i.e.  $17^{\circ}$  to  $22^{\circ}$  in Figure 6b, and  $26^{\circ}$  to  $33^{\circ}$  in Figure 6c), Sn signal strength is generally comparable to Pn signal strength.

In all of these comparisons, a major objection which could be made is that differences in source spectrums (and/or orientation of the source relative to the recording station) were not considered. Although all of the events occurred within the subducting margin of the Northwestern Pacific and the Pn, Sn phases used were generated by earthquakes having focal depths of

128 km or less, differences in source spectrums might be significant. We believe, however, that overall trends of the individual spectrums (Figure 4) used for the composite plots are similar (as opposed to specific details that may differ) and that such similarities could justify the general conclusions drawn from that data. We also note that source effects are minimized in those comparisons of composite Pn's and Sn's where both composites are for the same earthquakes (Figures 6b and 6c).

Another interesting feature of Pn,Sn phases is that the Pn wavetrain is much longer than the Sn wavetrain (Figure 2). Spectral analyses indicate that energy is lost at all frequencies in the later-arriving portions of these wavetrains, and that this loss is much greater in the Sn wavetrains than in the Pn wavetrains.

#### Ontong-Java Plateau Travel Paths

Spectrograms for some of the more interesting Pn phases with travel paths under the shallow Ontong-Java Plateau (as well as portions of the deep Northwestern Pacific Basin) are shown in Figure 7. (Refer to Table 1 and Figure 1). The most conspicuous feature of these spectrograms is that Sn phases are extremely weak, or absent, even though Pn phases are prominent.

Figure 8 compares the composite Pn spectrum for events having Ontong-Java Plateau travel paths (event nos. 19 through 25) to the composite Pn spectrum for events at comparable distances having Northwestern Pacific Basin travel paths (event nos. 15 through 18). The Northwestern Pacific Basin events have more Pn energy at higher frequencies than the Ontong-Java Plateau events, and, comparing Figures 2 and 7, the duration of the Pn wavetrains appears to be greater for the Northwestern Pacific Basin events.

In making such comparisons, the important question again arises of differences in source spectrums, in this instance for New Ireland-Solomon Island earthquakes and for Japan-Kuril Islands-Kamchatka earthquakes. It is not possible, however, to attribute the absence of Sn to differences in source spectrums, as Sn phases from New Ireland and the Solomons have been well recorded at Ponape (Figure 1) on the northern margin of the Ontong-Java Plateau [Walker, 1977]. Examples of such phases are shown in Figure 9. The absence of Sn at Wake would, therefore, appear to be a result of Sn's inability to propagate efficiently across the transition zone from the shallower Ontong-Java Plateau to the deeper Northwestern Pacific Basin. On the other hand, Sn's that have crossed this transition zone from the other direction (i.e., from earthquakes in the Marianas, Japan, the Kuriles, and Kamchatka) are well recorded at Ponape (Figure 9).

Another comparison of spectrums at Wake for the two differing types of travel paths (Northwestern Pacific Basin and Ontong-Java Plateau travel paths) was made for the later-arriving energy in the Pn wavetrains. For these comparisons, less energy at higher frequencies was present in those Pn's having appreciable parts of their travel paths across the Ontong-Java Plateau. These deficiencies and the corresponding absence of Sn for paths across the transition zone from the shallow Ontong-Java Plateau to the deep Northwestern Pacific Basin, suggest that the longer, stronger Pn phases observed for travel paths to Wake primarily across the Northwestern Pacific Basin may be the result of more efficient conversions of Pn to Sn.



## Concluding Remarks

The phenomenon of high-frequency Pn,Sn propagation is emerging as a major unresolved property of the oceanic crust and/or mantle. Others have described high-frequency Pn,Sn propagation as "a challenge remaining to the theoretician" [Richards, 1979] and as "the challenge to both explosion and earthquake seismology for the coming decade" [Hirn et al., 1973]. These descriptions are supported not only by the unusual character of the phases but also by their probable occurrence throughout the world's oceans.

As important as recent efforts are to determine the mechanism of high-frequency Pn,Sn propagation [e.g., Stephens and Isacks, 1977; Menke and Richards, 1980; Sutton and Harvey, 1981; and Gettrust and Frazer, 1981], we believe many essential characteristics of Pn,Sn phases (especially at very high frequencies) are not well known, and that accurate quantification of those characteristics through the acquisition of additional high-quality data is greatly needed. We hope that this report will further familiarize seismologists with high-frequency Pn,Sn propagation and will be viewed as a preliminary attempt to quantify, in a relative sense, some of the essential characteristics of these phases. A summary of principal observations contained in this report follows.

- The apparent non-existence of normal, mantle-refracted P phases at distances less than about  $21^{\circ}$  ( $\approx 2300$  km).
- Frequencies as high as 30 and 35 Hz for Pn and Sn, respectively, at  $18.0^{\circ}$  (2002 km).
- Frequencies as high as 15 and 20 Hz for Pn and Sn, respectively, at  $29.4^{\circ}$  (3269 km).

- With increasing distance (i.e., from about  $20^{\circ}$  to  $30^{\circ}$ ), Sn phases not losing their high frequencies as rapidly as Pn phases do.
- Pn wavetrains longer than Sn wavetrains.
- The extreme weakness or absence of Sn phases for travel paths across the transition zone from the Ontong-Java Plateau to the Northwestern Pacific Basin, and the presence of Sn phases for travel paths in the opposite direction across this transition zone.
- More Pn energy at higher frequencies and longer, more energetic Pn wavetrains for travel paths primarily in the Northwestern Pacific Basin than for travel paths across the transition zone from the Ontong-Java Plateau to the Northwestern Pacific Basin.

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Western Pacific, Science, 199, 1333-1335, 1978.

TABLE 1. Epicentral Distances, Origin Times, Depths, and Magnitudes of Events 1 through 25 in Figure 1

Event No.	Distance, deg.	Date, day/mo/yr	Time	Depth, km	Magnitude, mb
1	17.8	08/07/80	17 04 15.1	54	4.8
2	18.0	11/07/80	09 42 00.2	33	5.3
3	18.7	09/06/80	19 23 33.3	33	5.6
4	19.0	08/12/79	12 58 55.2	51	5.5
5	19.8	16/12/79	10 50 48.0	96	5.0
6	20.1	26/03/80	07 22 37.0	45	5.5
7	20.7	01/11/80	04 40 37.7	109	5.6
8	20.9	17/12/79	07 28 48.2	33	5.1
9	21.2	15/01/80	05 23 25.7	120	5.1
10	21.7	29/11/79	17 08 21.3	109	5.4
11	24.9	11/12/79	17 26 22.1	161	5.9
12	25.4	19/12/80	23 32 41.6	79	6.2
13	26.5	20/10/80	03 29 21.3	81	5.5
14	27.1	28/10/79	05 39 36.0	88	5.4
15	28.5	23/02/80	05 51 03.5	47	6.4
16	28.5	01/01/81	10 32 13.1	53	6.2
17	29.4	26/11/80	23 48 59.9	77	5.8
18	32.7	22/08/79	18 28 55.7	128	5.5
19	28.0	12/02/80	03 20 23.2	75	5.9
20	28.0	13/08/79	03 03 47.9	88	5.8
21	28.6	14/05/80	11 26 00.6	57	6.1
22	28.8	28/09/80	18 25 59.7	68	6.0
23	30.4	06/11/79	11 38 31.5	30	6.0
24	31.1	23/10/79	09 51 06.7	22	6.1
25	31.1	22/02/80	21 15 42.1	68	5.9

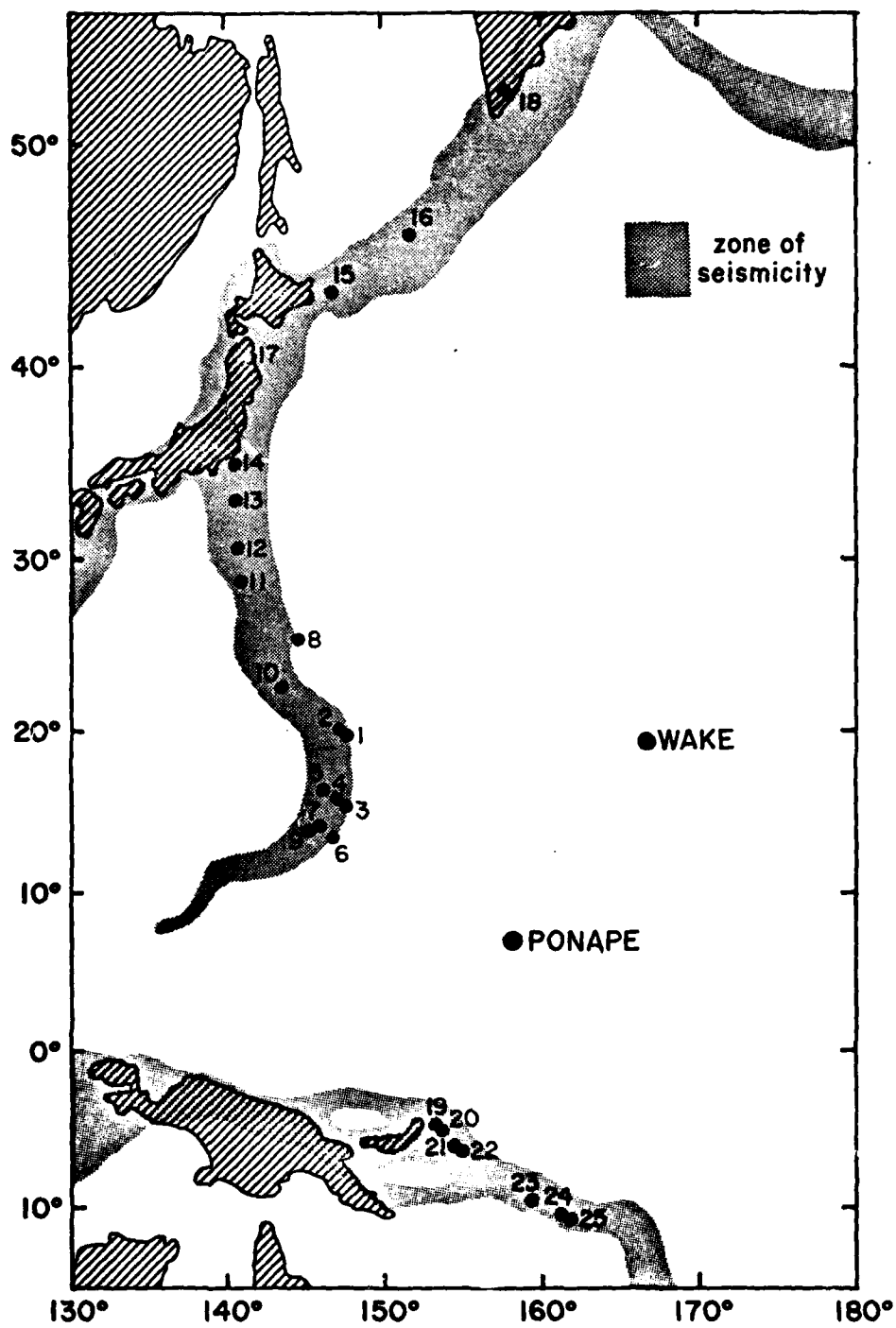
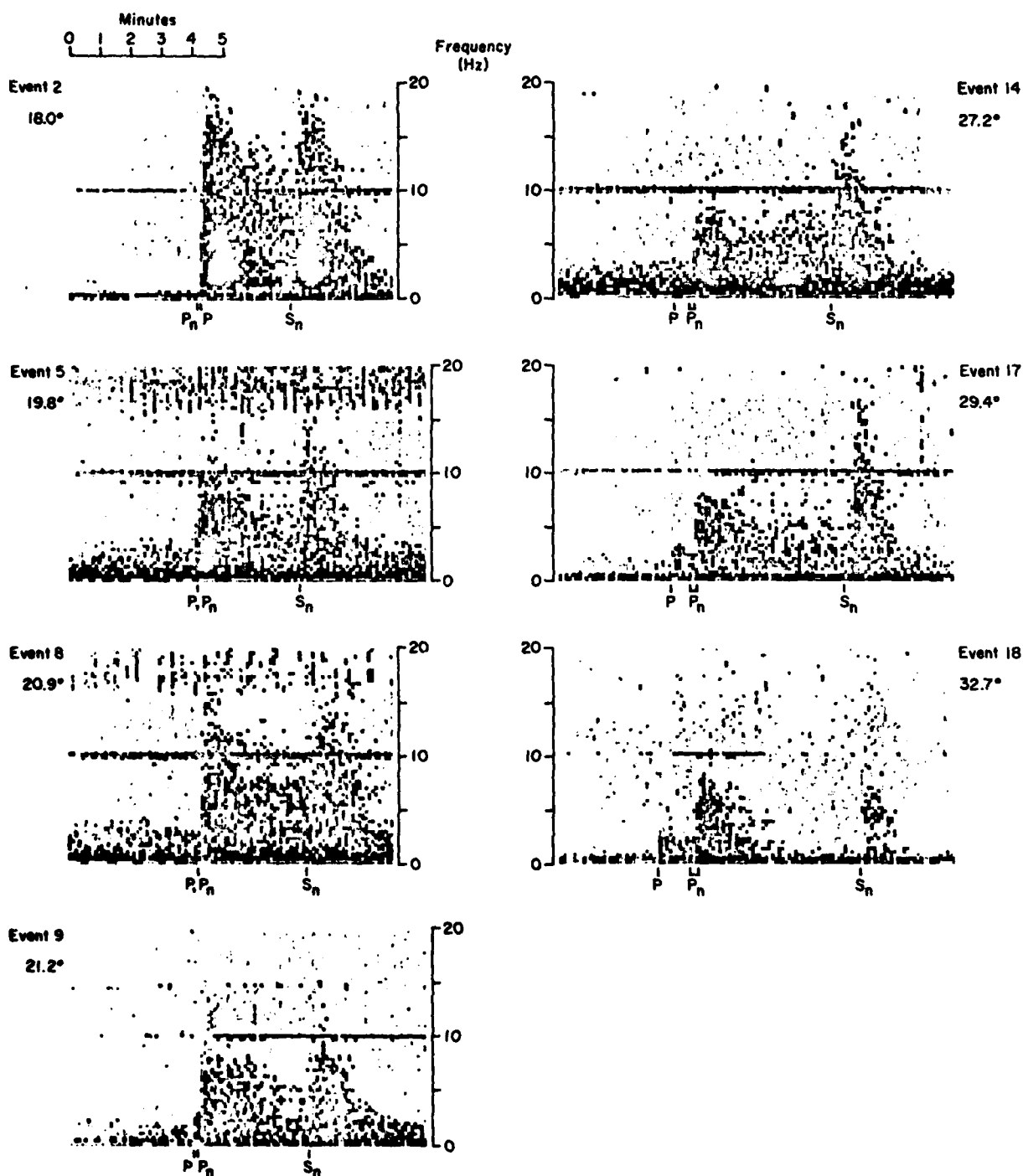


Fig. 1. Epicenter location map.



**Fig. 2.** Spectrograms for some earthquakes having travel paths under the Northwestern Pacific Basin. The contour interval is 8 db. Expected times of arrivals are based on either the Jeffreys-Bullen tables (1958) for P or Pn/Sn travel time curves from Walker (1977). The line at 10 Hz is due to time code cross talk.

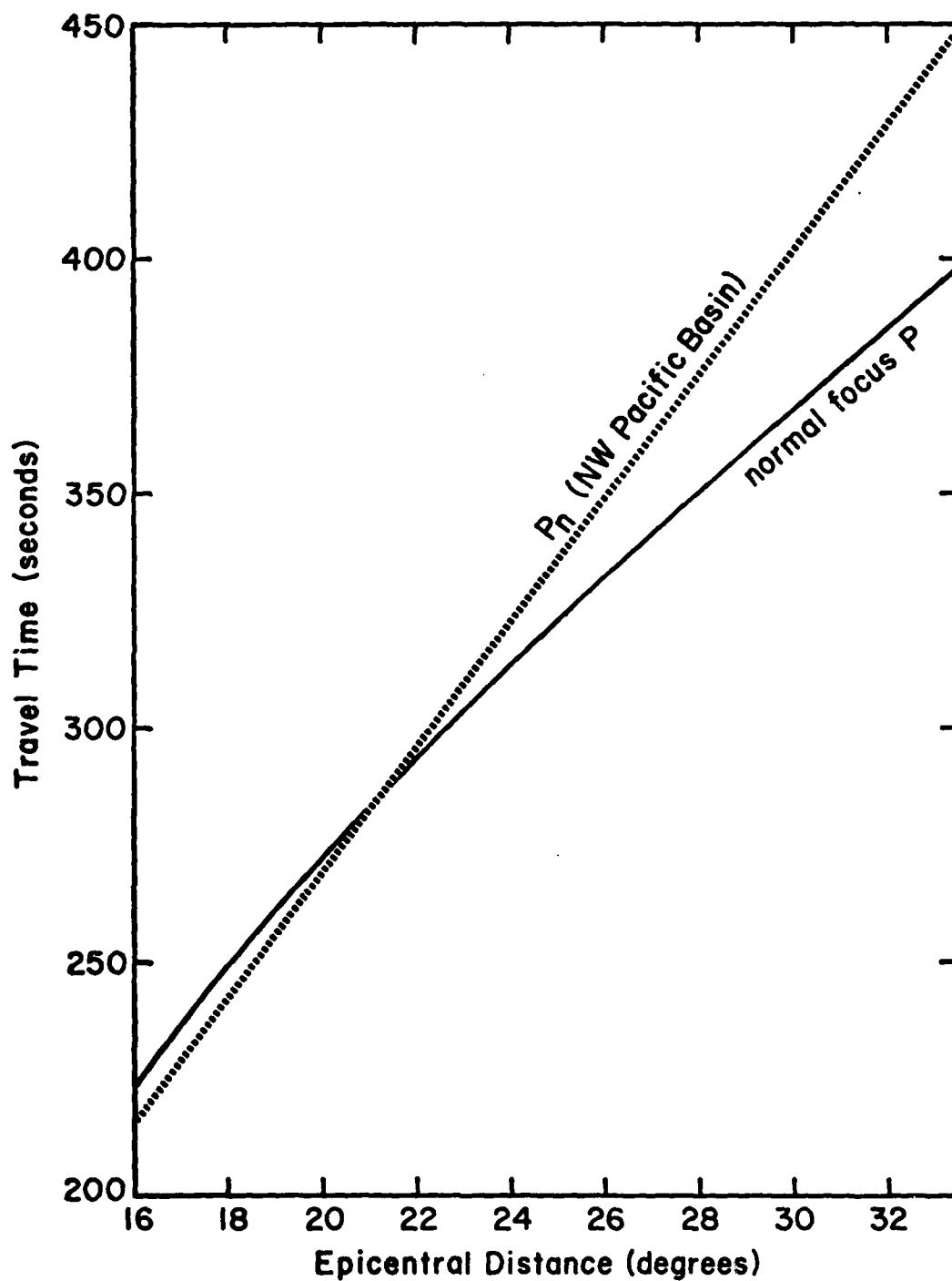
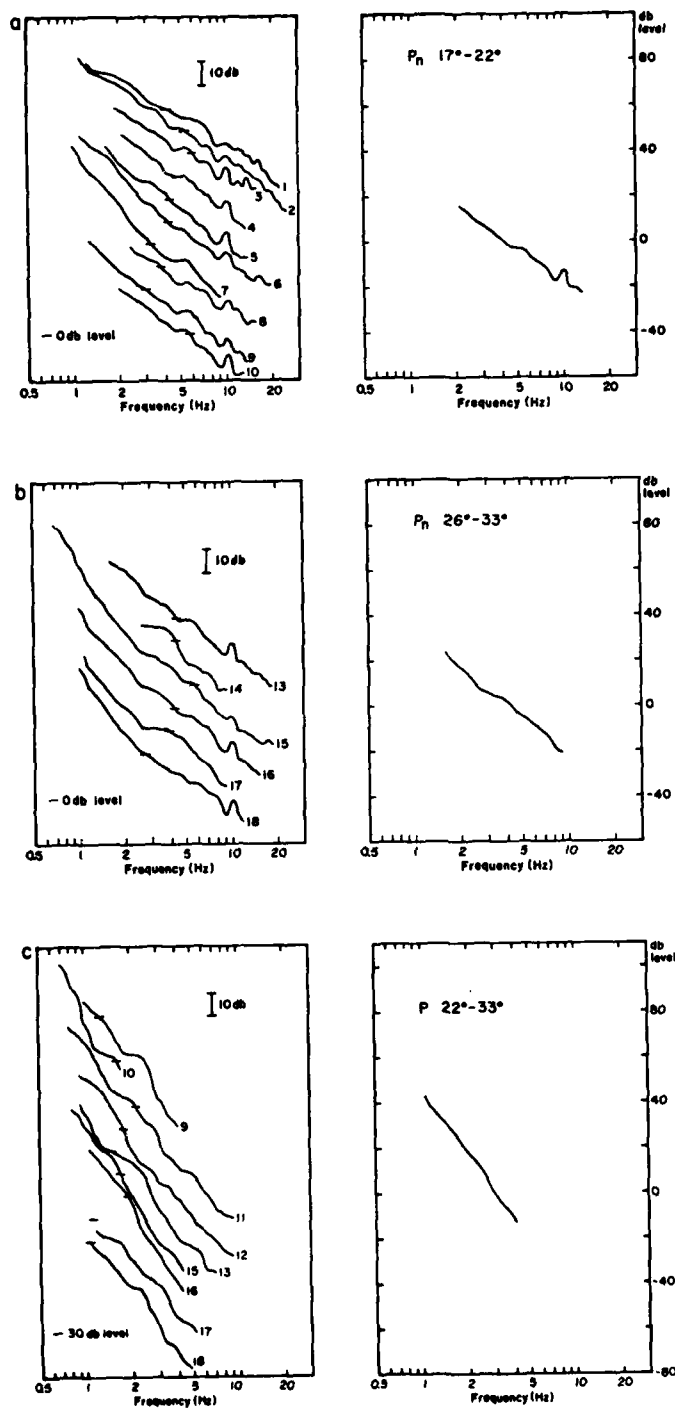


Fig. 3. Travel time curves for normal, mantle-refracted P phases and for Pn phases. P times are taken from Jeffreys and Bullen [1958] and Pn times are taken from Walker [1977].





**Fig. 4.** Individual and composite spectra for arrivals where (a) both  $P_n$  and  $P$  might be suspected of being present, at distances from about 17° to 22°, (b) only  $P_n$  is known to exist at distances from about 26° to 33°, and (c) only  $P$  is known to exist, at distances from about 22° to 33°. The peaks at 10 Hz are due to time code cross talk.

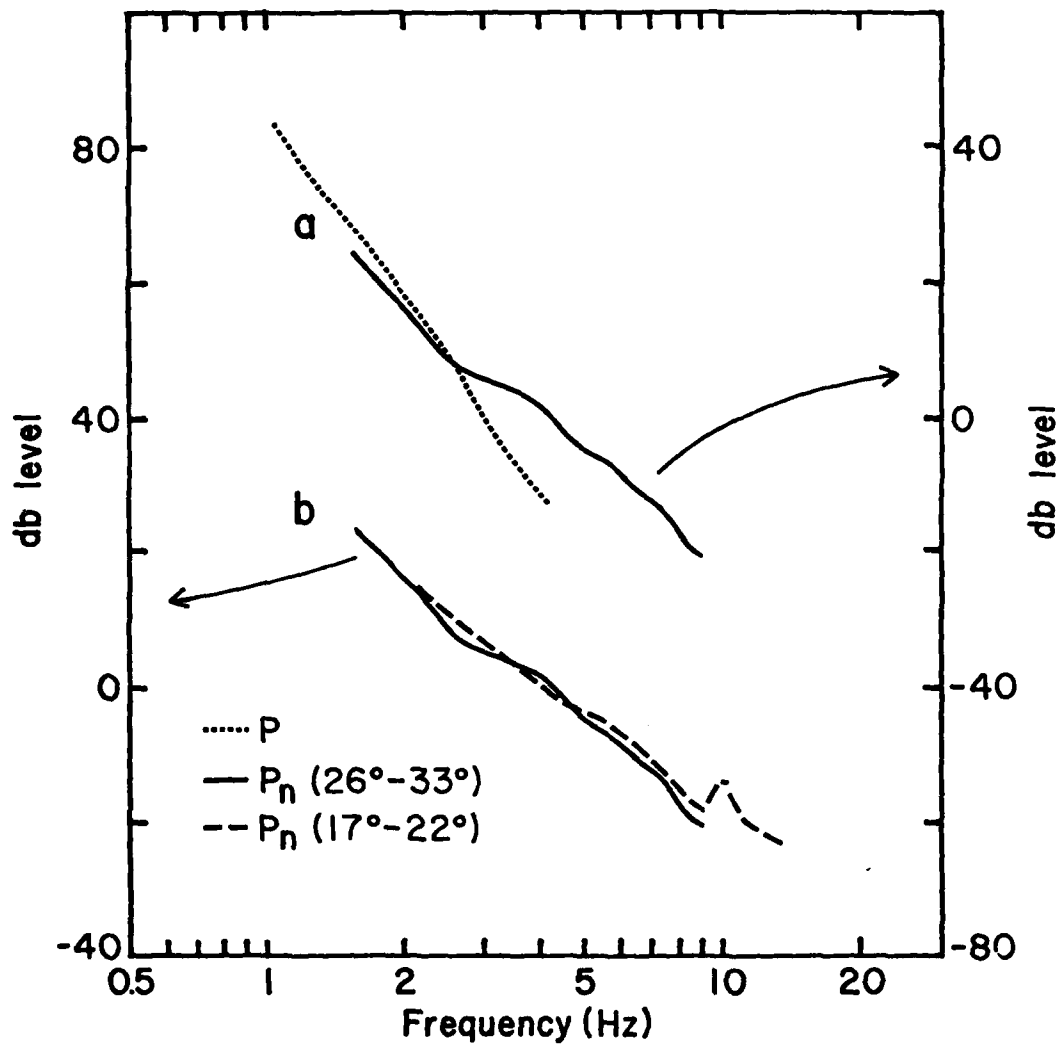


Fig. 5. Comparisons of composite spectrums: (a) P and the  $26^\circ$  to  $33^\circ$   $P_n$ , and (b) the  $17^\circ$  to  $22^\circ$   $P_n$  and the  $26^\circ$  to  $33^\circ$   $P_n$ .

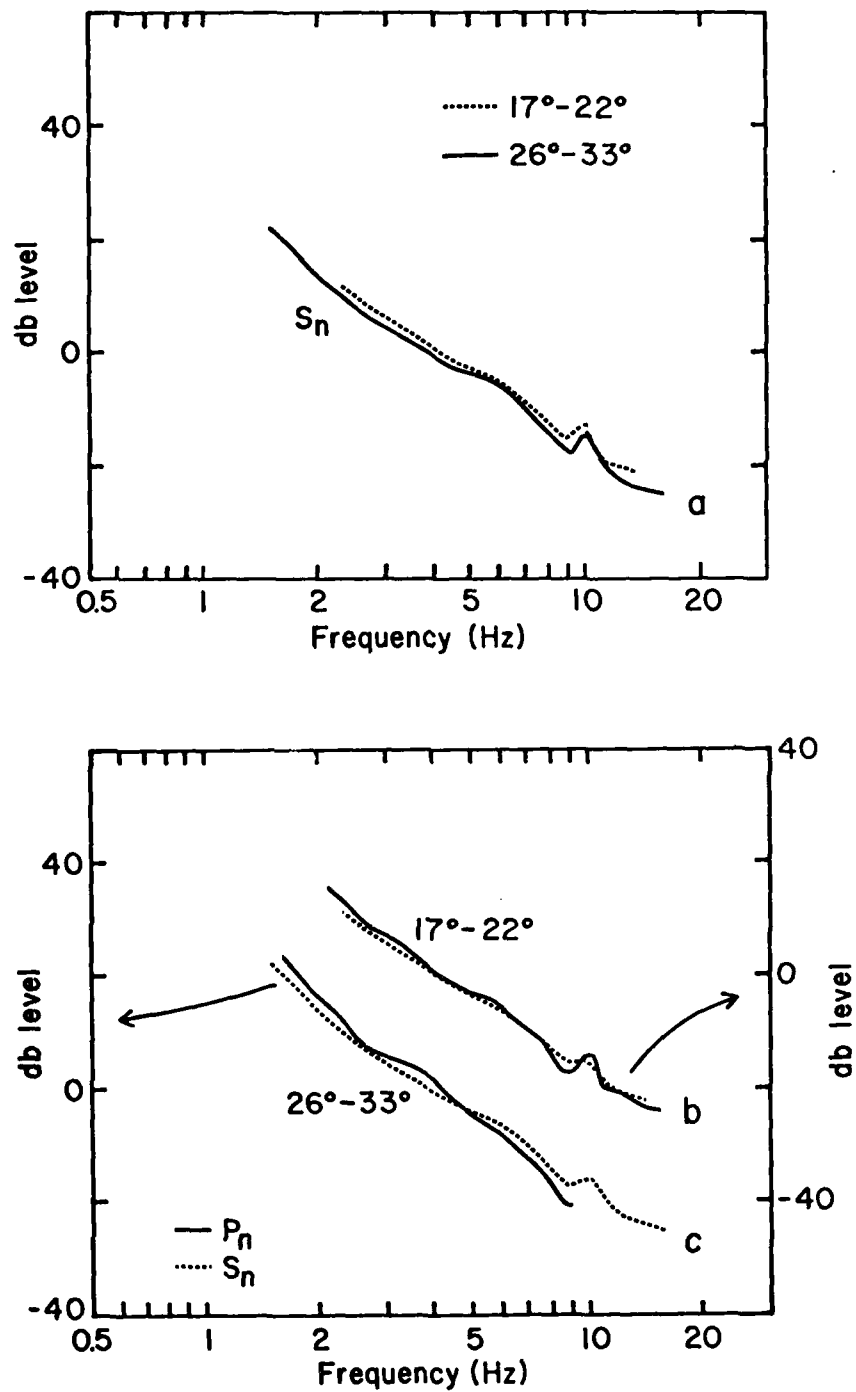


Fig. 6. Composite spectrums of  $S_n$  phases for those earthquakes having their  $P_n$  phases plotted in Figures 4a and 4b. Comparisons of spectrums are made for the two  $S_n$  composites to one another (a), and for each of the  $S_n$  composites to their respective  $P_n$  composite (b and c).

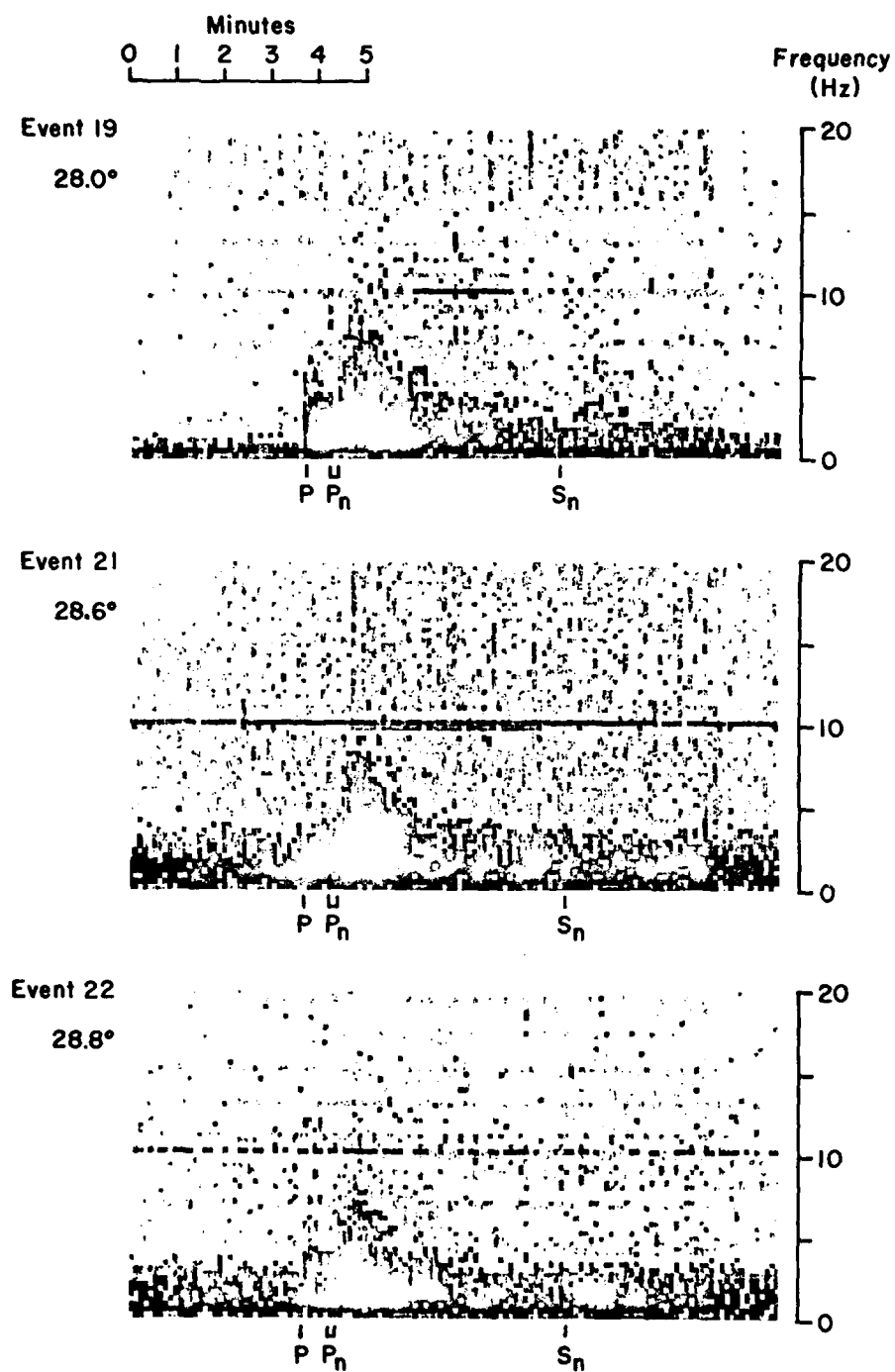


Fig. 7. Some spectrograms for earthquakes having travel paths under the Ontong-Java Plateau. The contour interval and the determinations of expected arrival times are the same as has been used in Figure 2.

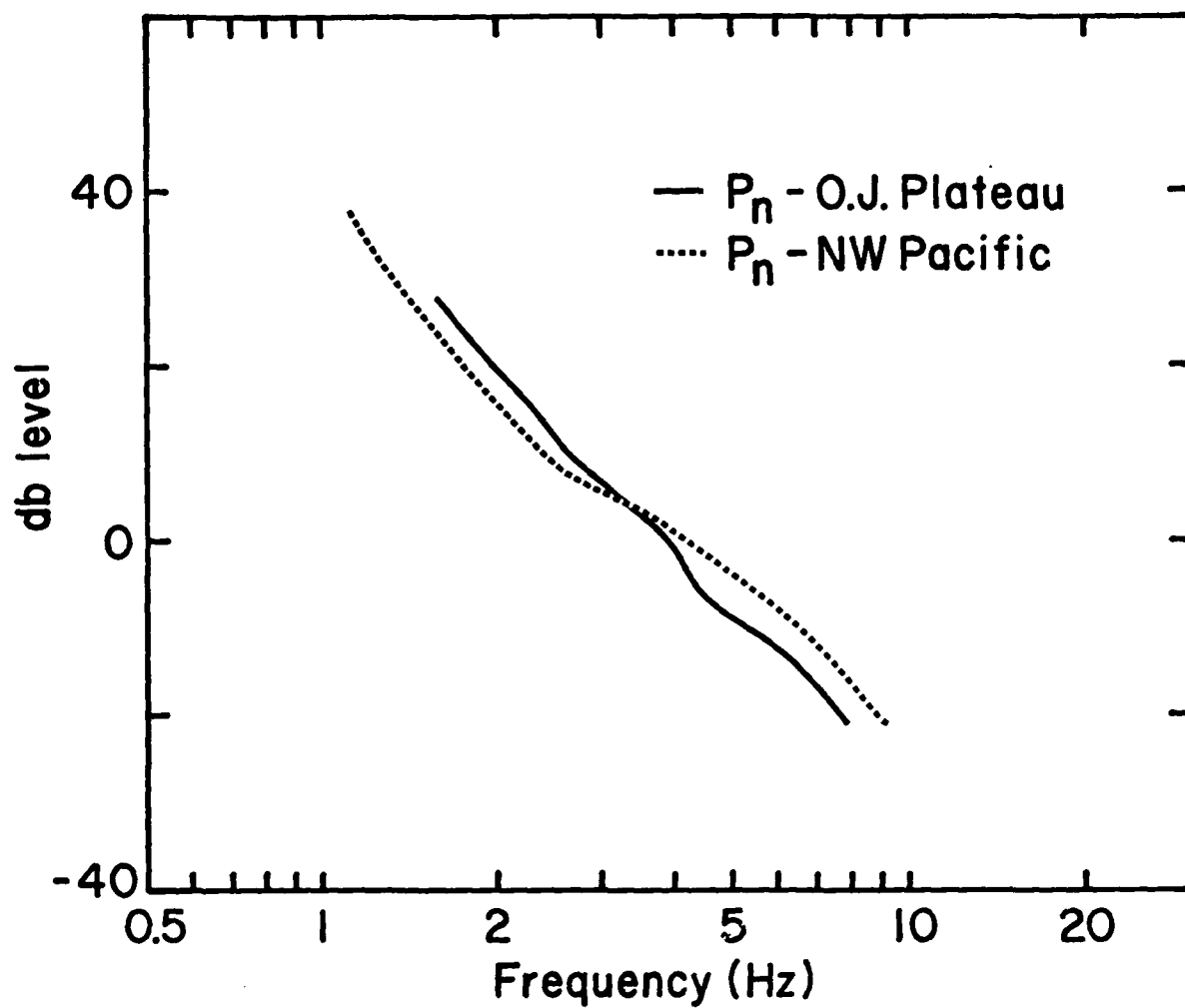


Fig. 8. Comparisons of composite  $P_n$  spectrums for events having travel paths across the Ontong-Java Plateau and the Northwestern Pacific Basin.

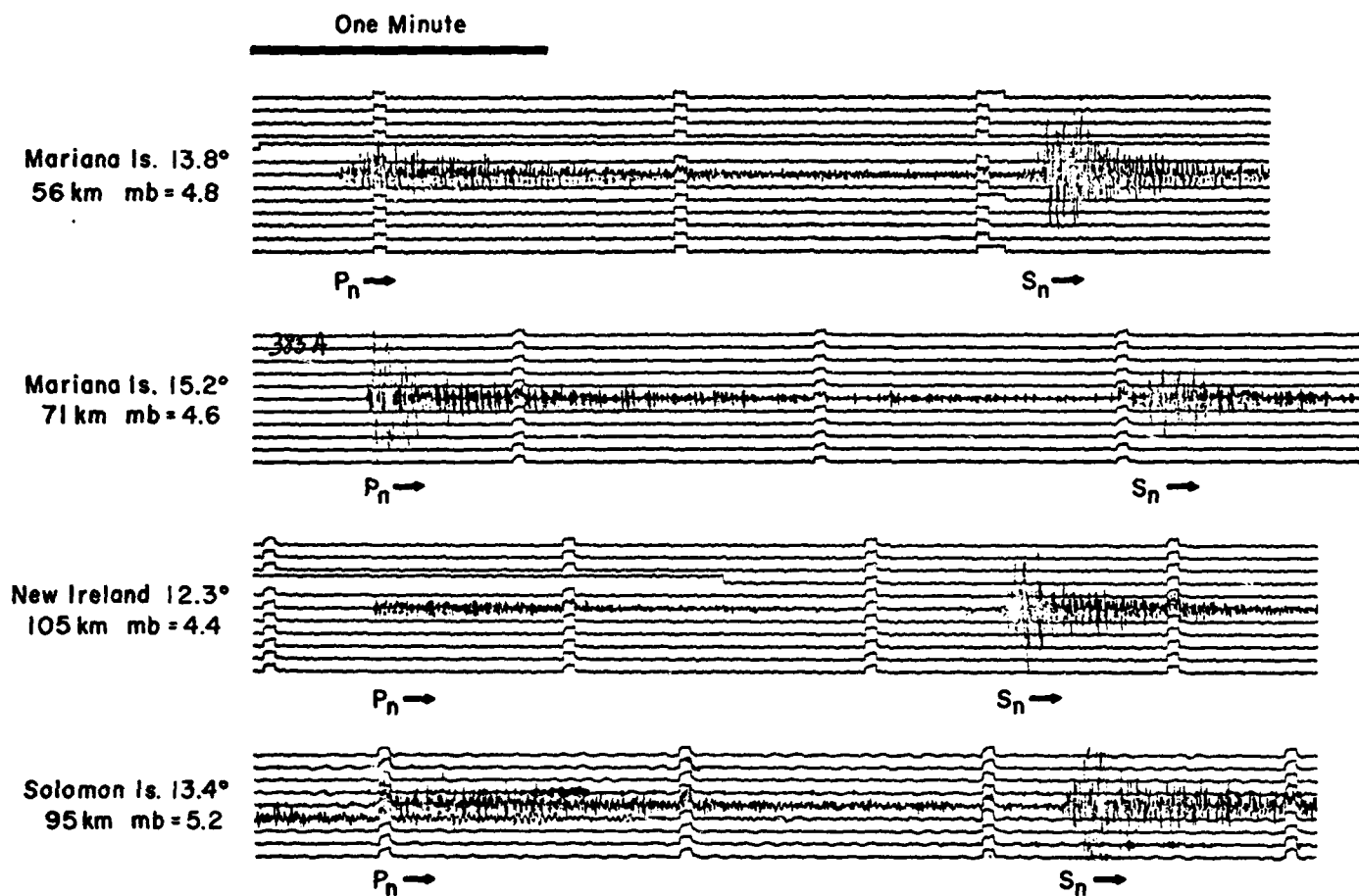


Fig. 9. P<sub>n</sub> and S<sub>n</sub> phases recorded at Ponape on the northern margin of the Ontong-Java Plateau.

## APPENDIX II

### A Description of Programs for Computing Individual and Composite Calibrated Spectra of Discrete Time Series with Variable Duration

by Charles S. McCreery

There exists a need for seismologists to quantitatively determine the spectral content of both continuous and transient signals in terms of actual earth motions. It would also be useful to compare groups of spectra from signals of a similar type for the purpose of finding a common shape and the range of variation of that shape. To address these needs, two programs, SPECT and MSPEC, have recently been developed. This report will describe the general features of these programs and explain how they are used.

Before these programs are used, the discrete time series data must be Fourier transformed by program FFTOBS (written by Fred Duennebier). The time series should be stored as a file on disk or tape and may be multiplexed with other time series data. Input parameters for this program, Figure 1, allow the user to specify which file and which blocks within that file he wants, which multiplexed channel is to be transformed, and if decimation of the data is required. Continuous but non-overlapping 512 point discrete fast Fourier transforms (FFT's) are then performed on the time series data. The output consists of a file containing blocks of 256 pairs of numbers--the real and imaginary parts of the transform. It is these FFT files which are used as input to SPECT and MSPEC.

Another file which is used as input to SPECT and MSPEC is the calibration file. This file contains 256 db values which, when subtracted from the corresponding 256 power spectral estimates (in db's re 1 digital unit), yield the units of ground motion (or whatever units are most useful) for each frequency. This calibration may be different for each seismic instrument, for each type of unit, or for each Nyquist frequency of the digitized

data. The calibration file may be formed using interactive program INCAL. The actual determination of these 256 calibration values can be accomplished by several methods which will not be discussed here. A sample calibration file is shown in Figure 2.

Sample input parameters for program SPECTare shown in Figure 3. This program will accept up to five files (or block ranges) of FFT input data--one for noise and four for signal. The program determines the average power level per block when more than one block of spectral data is used. Important plotting options which are available are as follows:

- A. Smoothing. At each center frequency,  $F$ , of the 256 spectral estimates, power is summed over the width of the smoothing boxcar,  $W$ , from  $F-0.5W$  to  $F + 0.5W$ .
- B. Noise Removal. For each frequency, the power of the noise is removed from the power of the signal (which is assumed to be actually the signal plus the noise). Only signal data above the threshold is plotted.

The option for numeric output is used to create a file containing spectral data for use by program MSPEC. Some samples of spectrums created by this program are shown in Figures 4-6.

Sample input parameters for program MSPEC are shown in Figure 7. Input spectral data is from the numeric output file generated by program SPECT. This program will compute an average spectrum from the group of spectrums specified. Before the averaging is done however, the user may smooth the data and/or remove the noise. If noise removal is specified, only signal data which exceeds the threshold is used to compute the average spectrum and its standard deviation. (This means that at least 2 spectra must have



significant data at any given frequency for the composite spectrum to have a mean and standard deviation at that frequency.) Some sample plots illustrating these features are shown in Figures 8-9.

An important special feature of MSPEC is normalization of the individual spectra before computing standard deviations on the composite spectrum. This feature was designed to show the stability (or non-stability) of the spectral shape, independent of overall spectral level. Within a specified frequency range, a mean db value is computed for each spectrum as well as for the group of spectra. The individual spectra are then normalized by subtracting the difference between their mean db value and the mean db value for the group, from each point in the spectrum. This is a way to "bring the curves together" for the purpose of showing the common spectral shape. Standard deviations are then computed for this data. (Note that if noise removal is used, data points for all curves, within the normalization frequency range, must be above the threshold.) Sample plots illustrating these features are shown in Figures 10-11.

```

*** FAST FOURIER POWER SPECTRUM - 256 ESTIMATES ***
INPUT START FILE #      1:  STARTING WITH 1
END FILE #              1:
OUTPUT START FILE #     1:
STARTING BLOCK #        001:  =1 WHEN DOING MORE THAN 1 FILE
END BLOCK #             9999:  =large number WHEN DOING >1 FILE
# OF CHANNELS IN DATA: 04:
# OF CHANNEL NEEDED:    04:
DECIMATION FACTOR:      01:  1=ALL POINTS, 2=EVERY OTHER, ....
HEADER LENGTH:          00:
WINDOW?MEAN?           1:  1=REMOVE MEAN AND DO WINDOW, 0 NO
***** I N F F T O :  INPUT PARAMETERS FOR XFTOBS *****
EOF.

```

Figure 1. Sample input parameters for program FFTOBS.

PROJECT: WAKE '79 PROJECT - HIG DAN WALKER / CHIP MCCREERY  
 INSTR: OBS TYPE CASSETTE - 4 CHANNELS - 1 WEEK / CASSETTE  
 SENS: 1 MICROBAR  
 TRANSMIT FREQUENCY: 40.00HZ

LIST FREQUENCY		40.00HZ	
-49.00	-22.00	-7.00	5.00
29.83	33.00	34.90	36.80
44.70	45.80	46.90	48.00
50.75	51.30	51.85	52.40
54.55	54.90	55.25	55.60
57.25	57.50	57.75	58.00
59.20	59.50	59.65	59.80
60.85	60.70	60.85	61.00
61.50	61.60	61.70	61.80
62.10	62.13	62.17	62.20
62.37	62.40	62.43	62.47
62.63	62.67	62.70	62.73
62.90	62.93	62.97	63.00
63.25	63.30	63.35	63.40
63.65	63.70	63.75	63.80
64.05	64.10	64.15	64.20
64.45	64.50	64.55	64.60
64.85	64.90	64.95	65.00
65.12	65.15	65.17	65.20
65.34	65.35	65.37	65.40
65.57	65.55	65.57	65.60
65.73	65.75	65.76	65.80
65.92	65.95	65.97	66.00
66.25	66.30	66.35	66.40
66.80	66.90	67.00	67.10
68.80	69.00	69.20	69.40
70.40	70.60	70.80	71.00
72.12	72.35	72.57	72.80
73.92	74.15	74.37	74.60
75.78	76.06	76.34	76.63
78.03	78.31	78.59	78.83
14.00	14.00	14.00	14.00
19.00	19.00	19.00	19.00
23.50	23.50	23.50	23.50
25.67	25.67	25.67	25.67
40.60	40.60	40.60	40.60
48.55	48.55	48.55	48.55
52.95	52.95	52.95	52.95
55.95	55.95	55.95	55.95
58.25	58.25	58.25	58.25
60.10	60.10	60.10	60.10
61.10	61.10	61.10	61.10
62.00	62.00	62.00	62.00
62.23	62.23	62.23	62.23
62.27	62.27	62.27	62.27
62.53	62.53	62.53	62.53
62.77	62.77	62.77	62.77
63.05	63.05	63.05	63.05
63.45	63.45	63.45	63.45
63.85	63.85	63.85	63.85
64.25	64.25	64.25	64.25
64.65	64.65	64.65	64.65
65.02	65.02	65.02	65.02
65.22	65.22	65.22	65.22
65.42	65.42	65.42	65.42
65.62	65.62	65.62	65.62
65.82	65.82	65.82	65.82
66.05	66.05	66.05	66.05
66.45	66.45	66.45	66.45
67.20	67.20	67.20	67.20
68.40	68.40	68.40	68.40
69.60	69.60	69.60	69.60
71.22	71.22	71.22	71.22
73.02	73.02	73.02	73.02
74.82	74.82	74.82	74.82
76.91	76.91	76.91	76.91
79.16	79.16	79.16	79.16
79.44	79.44	79.44	79.44
79.72	79.72	79.72	79.72
80.00	80.00	80.00	80.00

Figure 2. Sample calibration file for programs SPECT and MSPEC.

```

*****
*** INPUT - INPUT PARAMETER FILE FOR PROGRAM SPECT (LEN 40) ***
*****
* CALIBRATION AREA NAME (START AFTER COLON)          :CALFILE *
* FILE NUMBER WITHIN CALIBRATION AREA                02: *
* QUIET FREQUENCY OF THE DATA (HZ*10)              00400: *
* PLOTTING PARAMETERS (T-PLOT, F-NO PLOT)            T: *
* FREQUENCY SCALE (T-LINEAR, F-LOG)                  F: *
* LOWER FREQUENCY LIMIT (HZ*10)                     00005: *
* UPPER FREQUENCY LIMIT (HZ*10)                      00350: *
* LOWER DB LIMIT (INTEGER)                           -0060: *
* DB'S PER HALF INCH (INTEGER)                       00010: *
* BOXCAR SMOOTHING? (T-YES, F-NO)                    T: *
* BOXCAR WIDTH (HZ*100)                              00100: *
* NOISE REMOVAL (T-YES, F-NO)                         F: *
* THRESHOLD (S/N IN DB*10)                           00020: *
* NUMERIC OUTPUT? (T-YES, F-NO)                       F: *
* AREA NAME FOR NUMERIC OUTPUT                        :NWPSPECS *
* NOISE SPECTRUM (T-USED, F-NOT USED)                 T: *
* AREA NAME                                           :FCH4-034: *
* STARTING BLOCK (INTEGER)                           00001: *
* ENDING BLOCK (INTEGER)                             00025: *
* PLOT THE NOISE SPECTRUM? (T-YES, F-NO)              T: *
* SIGNAL SPECTRUM 1 (T-USED, F-NOT USED)              T: *
* NAME OF SIGNAL                                     :P *
* AREA NAME                                           :FCH4-034: *
* STARTING BLOCK (INTEGER)                           00042: *
* ENDING BLOCK (INTEGER)                             00043: *
* PLOT THIS SPECTRUM? (T-YES, F-NO)                  T: *
* SIGNAL SPECTRUM 2 (T-USED, F-NOT USED)              T: *
* NAME OF SIGNAL                                     :PN *
* AREA NAME                                           :FCH4-034: *
* STARTING BLOCK (INTEGER)                           00044: *
* ENDING BLOCK (INTEGER)                             00051: *
* PLOT THIS SPECTRUM? (T-YES, F-NO)                  T: *
* SIGNAL SPECTRUM 3 (T-USED, F-NOT USED)              T: *
* NAME OF SIGNAL                                     :SN *
* AREA NAME                                           :FCH4-034: *
* STARTING BLOCK (INTEGER)                           00079: *
* ENDING BLOCK (INTEGER)                             00085: *
* PLOT THIS SPECTRUM? (T-YES, F-NO)                  T: *
* SIGNAL SPECTRUM 4 (T-USED, F-NOT USED)              F: *
* NAME OF SIGNAL                                     :ABC *
* AREA NAME                                           :FCH4-001: *
* STARTING BLOCK (INTEGER)                           00010: *
* ENDING BLOCK (INTEGER)                             00040: *
* PLOT THIS SPECTRUM? (T-YES, F-NO)                  T: *
*****

```

Figure 3. Sample input parameters for program SPECT.

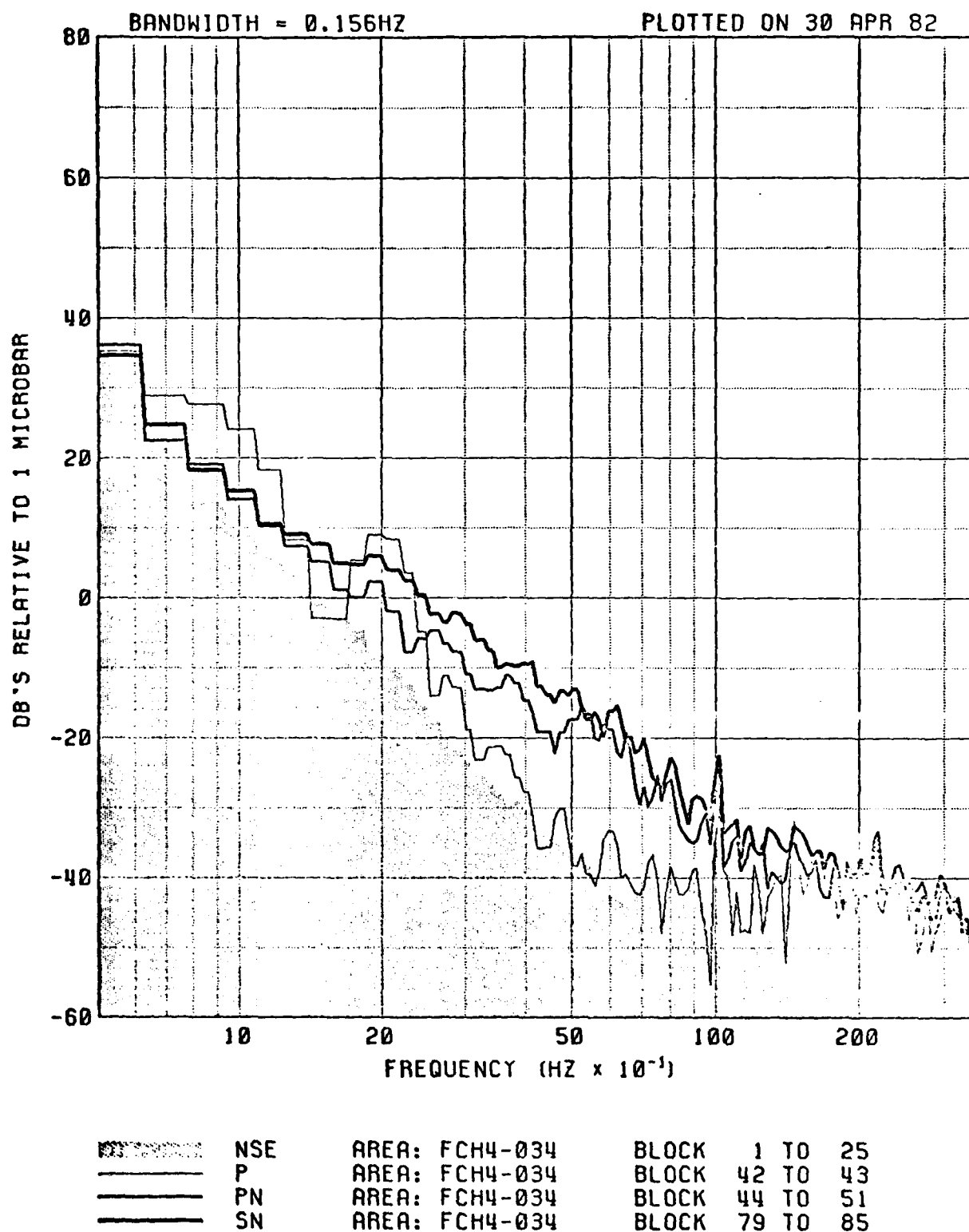


Figure 4. Sample spectral plot produced by program SPECT. Input parameters as shown in Figure 3, except no smoothing was performed.

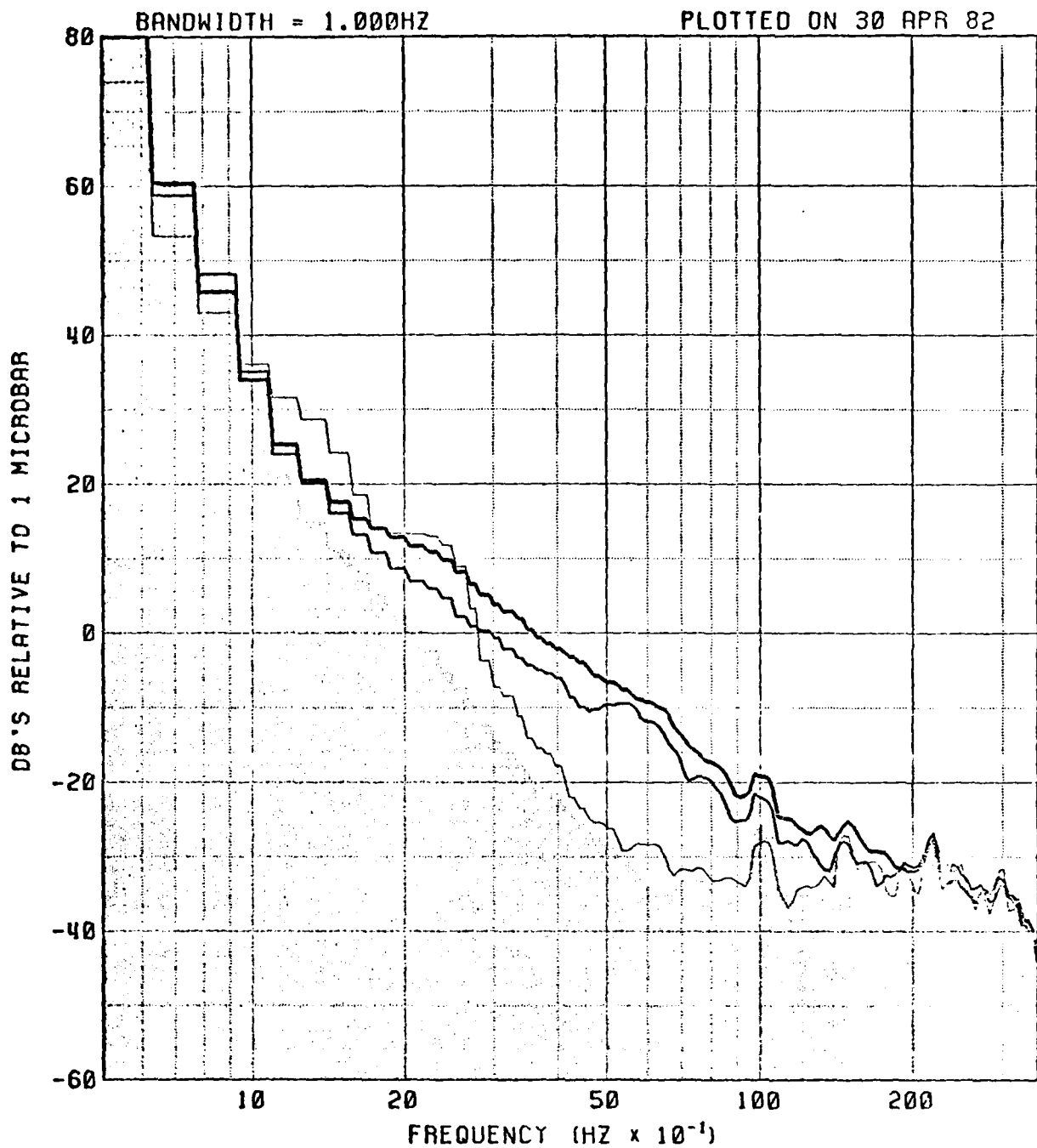
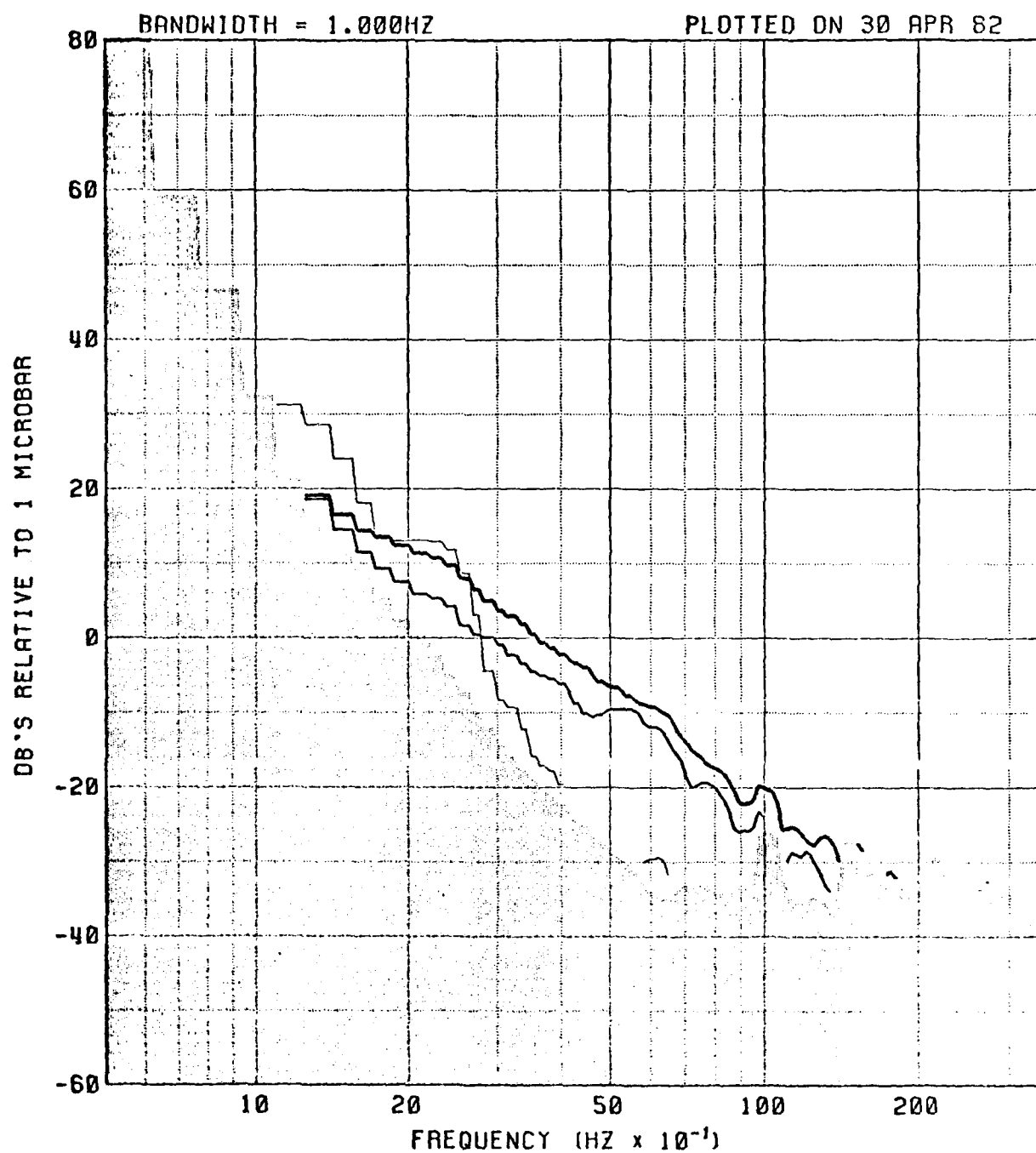


Figure 5. Same data as shown in Figure 4, except 1.0Hz smoothing was performed.



	NSE	AREA: FCH4-034	BLOCK 1 TO 25
	P	AREA: FCH4-034	BLOCK 42 TO 43
	PN	AREA: FCH4-034	BLOCK 44 TO 51
	SN	AREA: FCH4-034	BLOCK 79 TO 85

Figure 6. Same data as shown in Figure 5, but with noise removal performed.

```

* NYQUIST FREQUENCY OF THE DATA (HZ*10)          00400: *
* BOXCAR SMOOTHING? (T=YES, F=NO)                  F: *
* BOXCAR WIDTH (HZ*100)                            00100: *
* NOISE REMOVAL? (T=YES, F=NO)                      T: *
* THRESHOLD (S/N IN DB*10)                         00000: *
* NORMALIZATION OF INDIVIDUAL CURVES? (T=YES, F=NO) F: *
* LOWER FREQUENCY BOUND (HZ*10)                    00015: *
* UPPER FREQUENCY BOUND (HZ*10)                    00030: *
* PLOTTING PARAMETERS                               *
* FREQUENCY SCALE (T=LINEAR, F=LOG)                 F: *
* LOWER FREQUENCY LIMIT (HZ*10)                    00001: *
* UPPER FREQUENCY LIMIT (HZ*10)                    00200: *
* LOWER DB LIMIT (INTEGER)                          -0040: *
* DB'S PER HALF INCH (INTEGER)                     00010: *
* NAME OF THE AREA CONTAINING SPECTRAL DATA         :NUCSPECS: *
* NUMBER OF SPECTRAL SIGNALS (INTEGER)              00019: *
* SIGNAL 001 NOISE FILE 003: SIGNAL FILE 004:      *
* SIGNAL 002 NOISE FILE 005: SIGNAL FILE 006:      *
* SIGNAL 003 NOISE FILE 009: SIGNAL FILE 010:      *
* SIGNAL 004 NOISE FILE 011: SIGNAL FILE 012:      *
* SIGNAL 005 NOISE FILE 015: SIGNAL FILE 016:      *
* SIGNAL 006 NOISE FILE 017: SIGNAL FILE 018:      *
* SIGNAL 007 NOISE FILE 019: SIGNAL FILE 020:      *
* SIGNAL 008 NOISE FILE 025: SIGNAL FILE 026:      *
* SIGNAL 009 NOISE FILE 027: SIGNAL FILE 028:      *
* SIGNAL 010 NOISE FILE 029: SIGNAL FILE 030:      *
* SIGNAL 011 NOISE FILE 031: SIGNAL FILE 032:      *
* SIGNAL 012 NOISE FILE 035: SIGNAL FILE 036:      *
* SIGNAL 013 NOISE FILE 039: SIGNAL FILE 040:      *
* SIGNAL 014 NOISE FILE 045: SIGNAL FILE 046:      *
* SIGNAL 015 NOISE FILE 051: SIGNAL FILE 052:      *
* SIGNAL 016 NOISE FILE 053: SIGNAL FILE 054:      *
* SIGNAL 018 NOISE FILE 057: SIGNAL FILE 058:      *
* SIGNAL 019 NOISE FILE 061: SIGNAL FILE 062:      *
* SIGNAL 020 NOISE FILE 065: SIGNAL FILE 066:      *

SIGNAL: 1 AREA: FCH1-002 BLOCKS: 11 TO 12
SIGNAL: 2 AREA: FCH1-004 BLOCKS: 11 TO 13
SIGNAL: 3 AREA: FCH2-002 BLOCKS: 11 TO 13
SIGNAL: 4 AREA: FCH2-004 BLOCKS: 11 TO 13
SIGNAL: 5 AREA: FCH4-002 BLOCKS: 11 TO 12
SIGNAL: 6 AREA: FCH4-004 BLOCKS: 11 TO 12
SIGNAL: 7 AREA: FCH2-006 BLOCKS: 11 TO 12
SIGNAL: 8 AREA: FCH2-009 BLOCKS: 11 TO 12
SIGNAL: 9 AREA: FCH2-010 BLOCKS: 11 TO 12
SIGNAL: 10 AREA: FCH2-012 BLOCKS: 11 TO 12
SIGNAL: 11 AREA: FCH2-013 BLOCKS: 11 TO 12
SIGNAL: 12 AREA: FCH2-019 BLOCKS: 11 TO 20
SIGNAL: 13 AREA: FCH2-023 BLOCKS: 11 TO 13
SIGNAL: 14 AREA: FCH4-006 BLOCKS: 11 TO 12
SIGNAL: 15 AREA: FCH4-009 BLOCKS: 11 TO 12
SIGNAL: 16 AREA: FCH4-010 BLOCKS: 11 TO 13
SIGNAL: 17 AREA: FCH4-013 BLOCKS: 11 TO 14
SIGNAL: 18 AREA: FCH4-019 BLOCKS: 11 TO 16
SIGNAL: 19 AREA: FCH4-023 BLOCKS: 11 TO 12

```

Figure 7. Sample input parameters for program MSPEC.



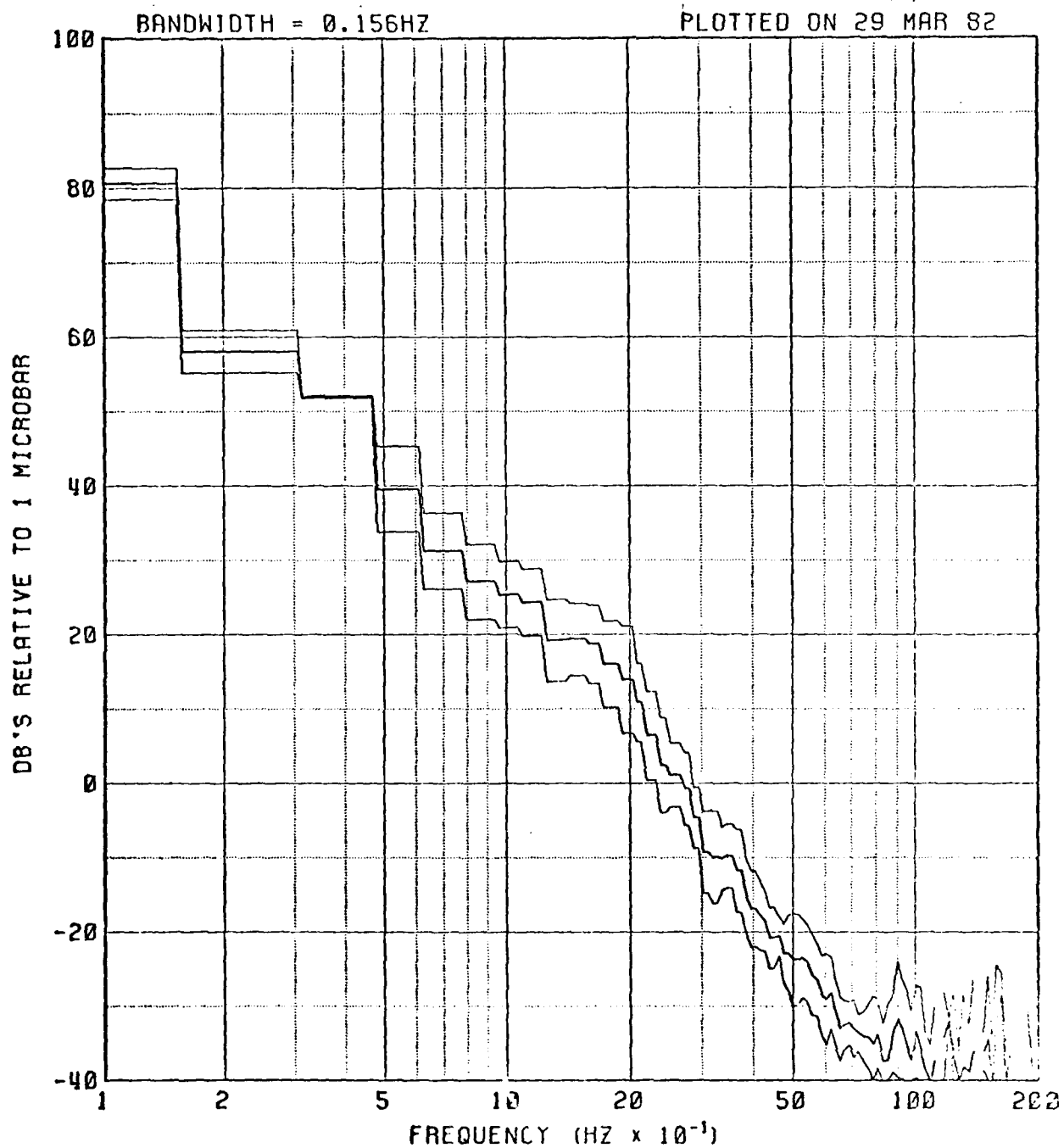


Figure 8. Sample plot produced by program MSPEC. Input parameters as shown in Figure 7.

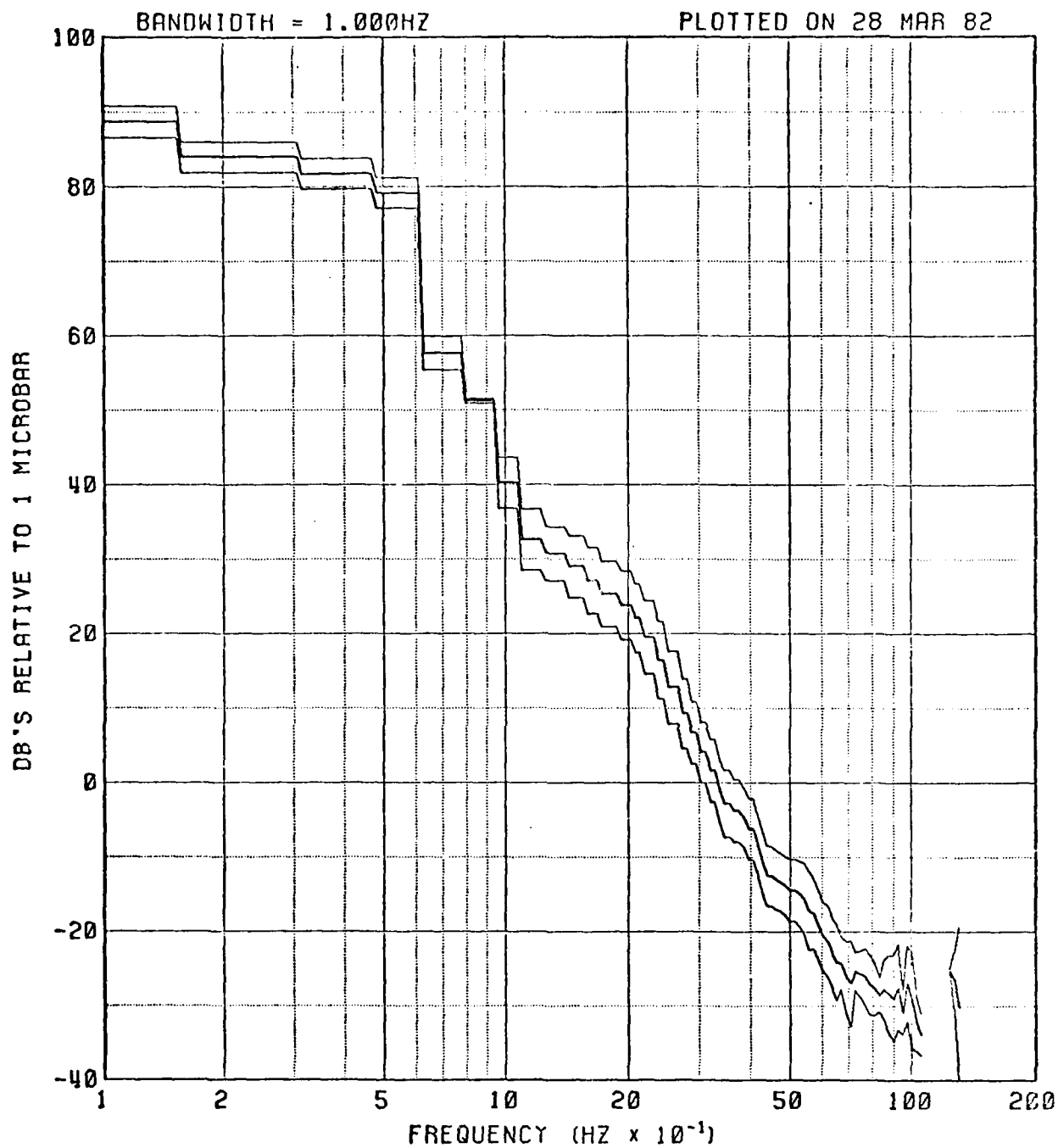


Figure 9. Sample plot produced by MSPEC. Input parameters the same as used for Figure 8, with 1.0Hz smoothing performed.

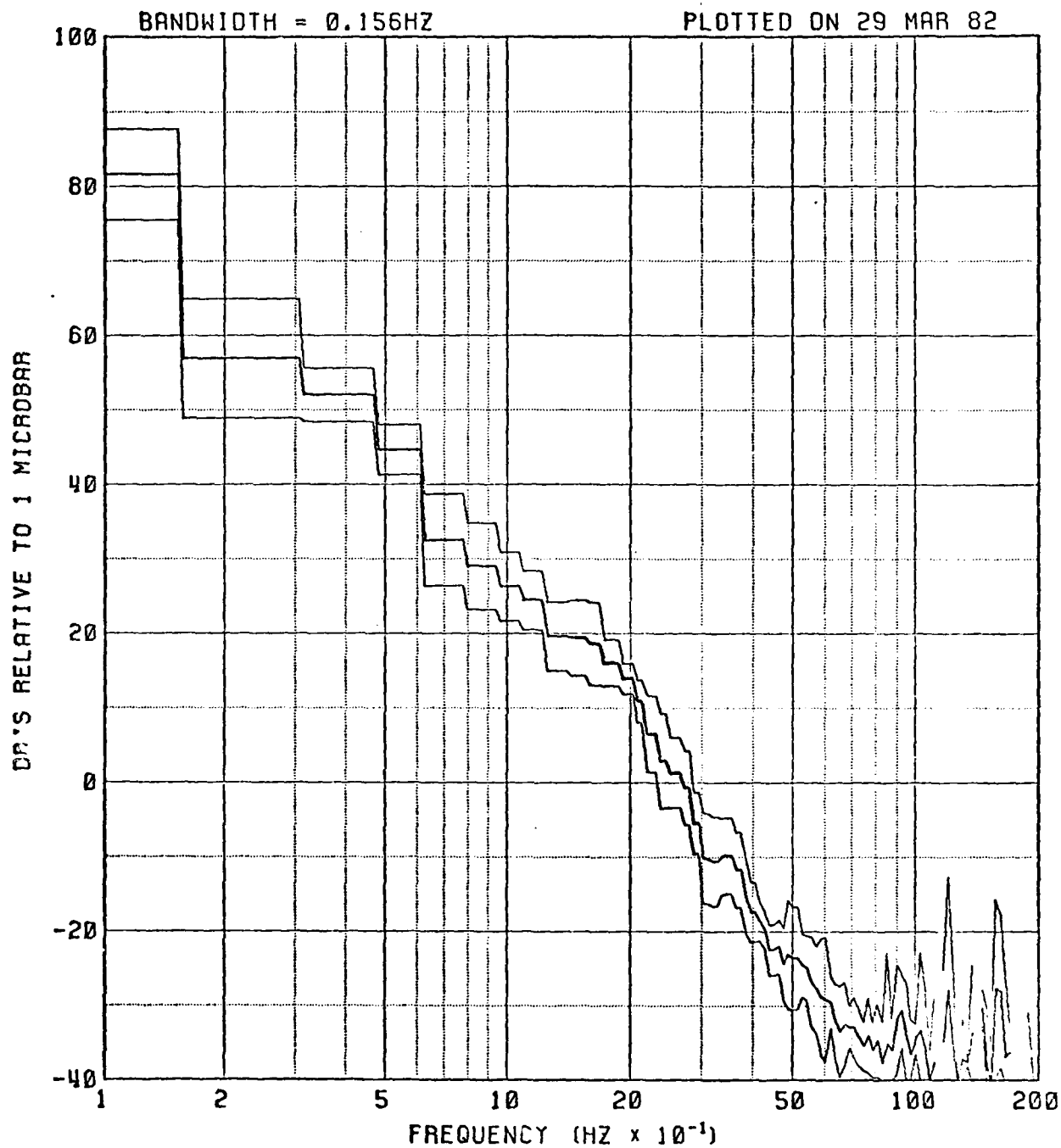


Figure 10. Same as Figure 8, except normalization performed from 1.5-3.0Hz.

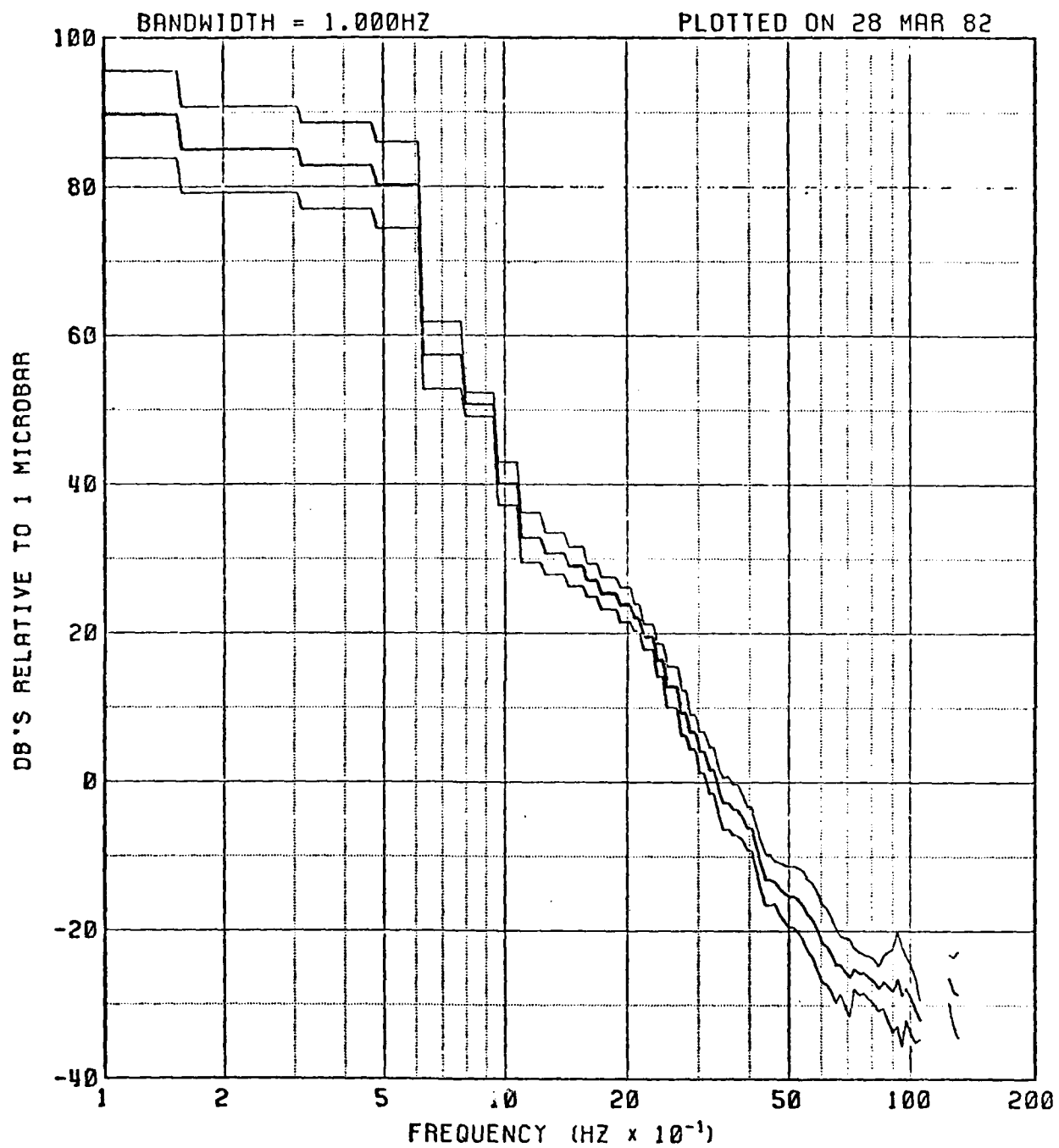


Figure 11. Same as Figure 9, with normalization performed from 1.5-3.0Hz.

APPENDIX III

Spectra of Nuclear Explosions, Earthquakes, and Noise from  
Wake Island Bottom Hydrophones

by

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(Submitted to JGR in May 1982)

Spectra of Nuclear Explosions, Earthquakes, and Noise from  
Wake Island Bottom Hydrophones

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Abstract. Spectral characteristics of P phases from shallow focus earthquakes and underground explosions, and of ocean bottom background noise, are examined using tape recordings of ocean bottom hydrophones near Wake Island from July 1979 through March 1981. Significant differences are found between spectra of large shallow focus earthquakes and explosions ( $5.7 \leq m_b \leq 6.3$ ) observed at  $61^\circ$ - $77^\circ$  epicentral distance. Explosions were found to have less energy at frequencies below 1.5 Hz and more energy at frequencies above 2.0 Hz. Earthquakes were found to have a spectral slope of -28 db/octave (relative to pressure) over the band 1-6 Hz. Explosions were found to have the same spectral slope over the band 2.2-6 Hz, but a different slope of -12 db/octave over the band 1.1-2.2 Hz. Ambient noise levels on the ocean bottom near Wake are found to be comparable to levels at the quietest continental sites for frequencies between 3 Hz and 15 Hz.

Introduction

In an earlier report (Walker, 1980) slow speed paper recordings of hydrophones located near Wake Island were used in a study of P phases from underground nuclear explosions and earthquakes at comparable distances. That study was prompted by: (a) the work of Evernden (1977) and Evernden and Kohler (1979), which showed that P phases recorded in the  $60^\circ$  to  $90^\circ$  distance

range from underground explosions were surprisingly rich in high-frequency energy (at least as high as 9 Hz); (b) the extreme sensitivity of the Wake hydrophones to high-frequency signals (Walker et al., 1978); and (c) the fact that most known underground test sites are in the 60° to 90° distance range from the Wake hydrophones. The major conclusion was that observable P phases were found for all Russian underground explosions with yields in excess of 270 kilotons, while no such phases were found for earthquakes of comparable or greater magnitude at similar distances. Principal limitations of the investigation were that: (a) the slow-speed paper recordings were not suitable for detailed spectral analyses of either the recorded signals or the noise; and (b) the filtering was not optimized for the recording of distant earthquakes and explosions. This report discusses the spectra of P phases from underground explosions and earthquakes, as well as the spectra of background noise, derived from recent tape recordings of the Wake Island ocean bottom (5.5 km depth) hydrophones.

#### Spectra of Underground Explosions and Natural Earthquakes

A list describing the earthquakes and explosions used in this study is given in Table 1. These events were chosen because they all: (a) occurred within 60° to 90° epicentral distance; (b) were shallow focus; (c) had large signal:noise ratios; and (d) did not exceed the dynamic range of the recording system. Figure 1 shows the spectra of some of these events, as well as composite spectra for the earthquake and explosion groups. The following differences in the spectral signatures between explosions and shallow focus earthquakes are evident: (a) lack of energy in explosion P relative to earthquake P at frequencies below 1.5 Hz, (b) change in spectral slope (corner frequency?) for explosions from -12 db/octave to -28 db/octave at

about 2.2 Hz, and (c) greater energy in explosion P relative to earthquake P at frequencies above 2.0 Hz, in spite of the fact that the average explosion magnitude (6.03) was less than the average earthquake magnitude (6.16).

#### Ocean Bottom Ambient Noise

The average background noise at the ocean bottom near Wake is shown in Figure 2 (labelled A). This average, along with its standard deviation, was determined from 52 samples of noise taken over 18 months of recording. Also plotted are an assortment of published noise curves for both ocean bottom and continental sites. When compared with continental sites, the Wake ambient noise level could be described as: (a) high for frequencies between 0.2 Hz and 1.5 Hz; (b) average for frequencies between 1.5 Hz and 3.0 Hz; and (c) low for frequencies between 3.0 Hz and 15.0 Hz.

The observed low noise levels at higher frequencies enhance the ability of the Wake hydrophones to detect seismic signals at those frequencies. In addition, high-frequency phases recorded on the deep ocean bottom, which traverse only a few kilometers of crust, are less attenuated (and distorted) than similar phases recorded on continents, which often traverse more than 40 km of crust. These factors (low noise levels and a thin crust) have enabled the Wake array to acquire some impressive recordings of underground nuclear explosions. Shown in Figure 3 is an Eastern Kazakh explosion at 73° with a body wave magnitude of 5.9. Its signal:noise ratio is approximately 50:1. Also shown in Figure 3 is a Western Siberia explosion at 77° with a body wave magnitude of 4.6.

This arrival is a composite of signals from two of the hydrophones which utilized the high level of coherence between a signal and its water



column multiple as well as between signals across the array (40 km between hydrophones) to enhance a weak arrival with less than 1.5:1 signal:noise to a prominent arrival with greater than 3:1 signal:noise.

#### Summary

Significant differences are found between the spectra of P phases from explosions and shallow focus earthquakes at  $61^{\circ}$ - $77^{\circ}$  epicentral distance. Explosion spectra exhibit a change in spectral slope at about 2.2 Hz from -12 db/octave to -28 db/octave relative to pressure. Earthquake spectra have a nearly constant slope of -28 db/octave over the range of 1 Hz to 6 Hz.

The spectra of ambient noise on the ocean bottom near Wake falls off at about -24 db/octave over the range of 0.3 Hz to 6 Hz. Between 3 Hz and 15 Hz the background noise levels are comparable to those at the quietest continental sites. These low noise levels permit the Wake bottom hydrophone array to be a good receptor for those earthquake and explosion generated seismic phases which are rich in high frequencies.

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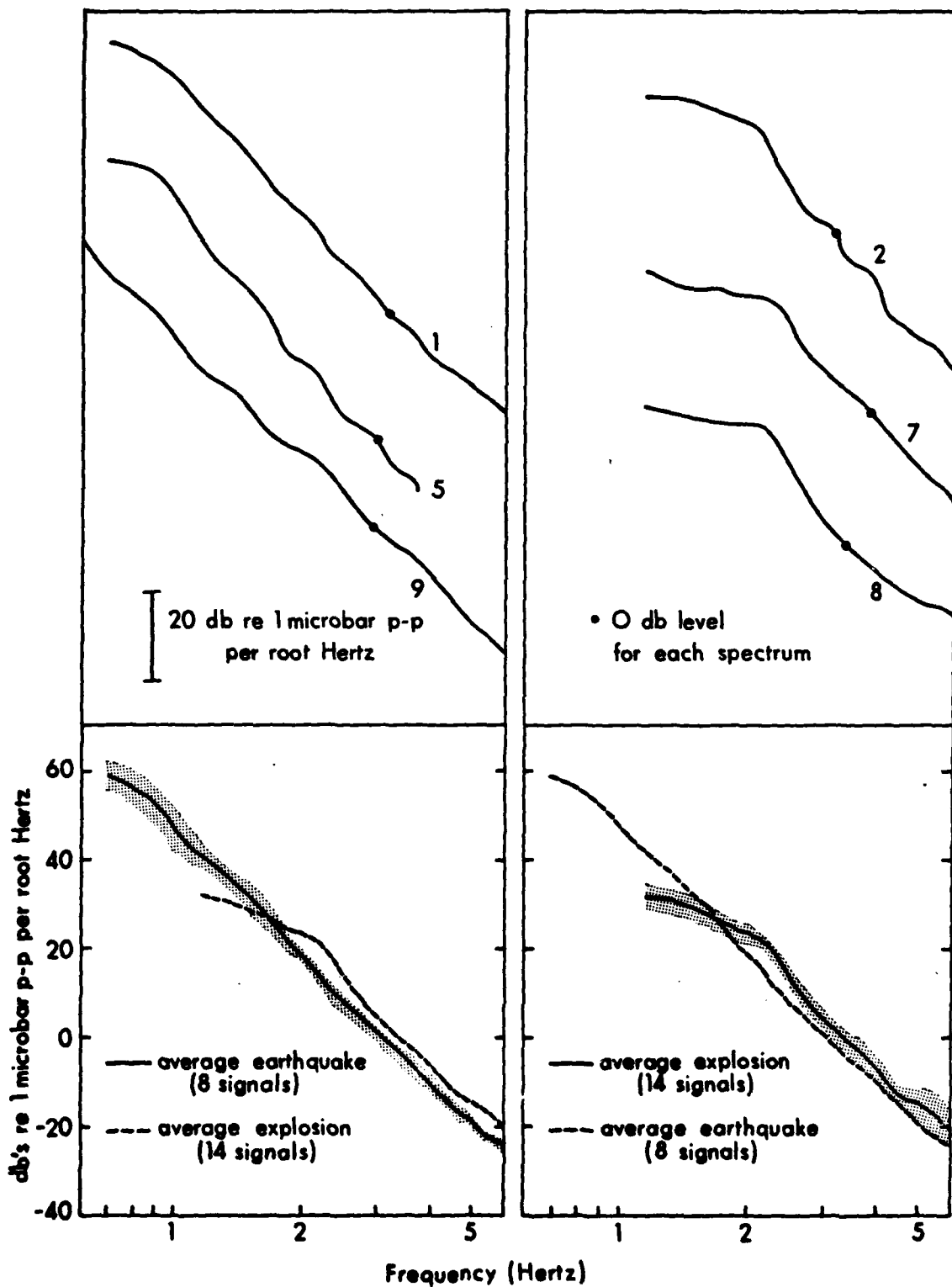
Table 1. Description of Events Used in Figure 1

Number	Date	Location	Distance (degrees)	Depth (km)	Magnitude (mb)	Type	Number of Hydrophones
1	07/24/79	S. of Java	65.7	31	6.3	Earthquake	3
2	08/04/79	E. Kazakh	73.2	0	6.1	Explosion	3
3	08/18/79	E. Kazakh	73.2	0	6.1	Explosion	3
4	09/24/79	Novaya Zemlya	76.7	0	5.7	Explosion	1
5	09/29/79	N. Sumatera	72.9	27	6.2	Earthquake	1
6	10/18/79	Novaya Zemlya	76.8	0	5.8	Explosion	1
7	10/28/79	E. Kazakh	73.2	0	6.0	Explosion	1
8	12/23/79	E. Kazakh	73.3	0	6.1	Explosion	1
9	07/29/80	Nepal	76.4	18	6.1	Earthquake	2
10	09/14/80	E. Kazakh	73.2	0	6.2	Explosion	2
11	10/12/80	E. Kazakh	73.2	0	5.9	Explosion	2
12	11/19/80	Sikkim	70.4	17	6.0	Earthquake	2

**Figure 1.** Sample spectra of P from shallow focus earthquakes and nuclear explosions are shown in the upper portion of this figure. Numbers refer to the event as described in Table 1. The composite spectrum of each group, an average with plus or minus one standard deviation, is shown in the lower portion of the figure. Before standard deviations were computed, individual spectrums were normalized by subtracting the difference between their mean db value over the range 1.5-3.0 Hz and the mean db value for all spectrums over the same frequency range from each point in the spectrum.

# Shallow Focus Earthquakes

# Explosions



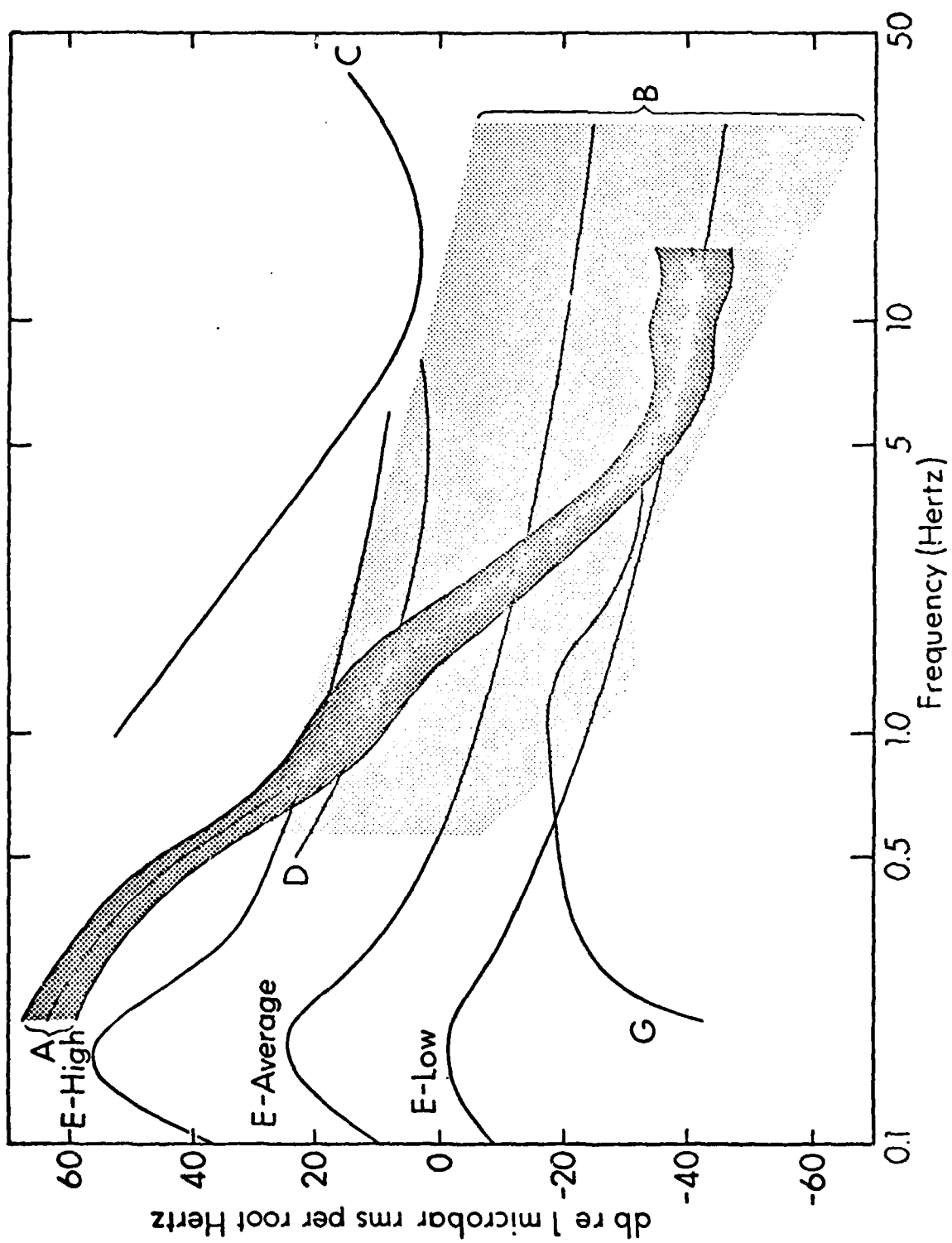
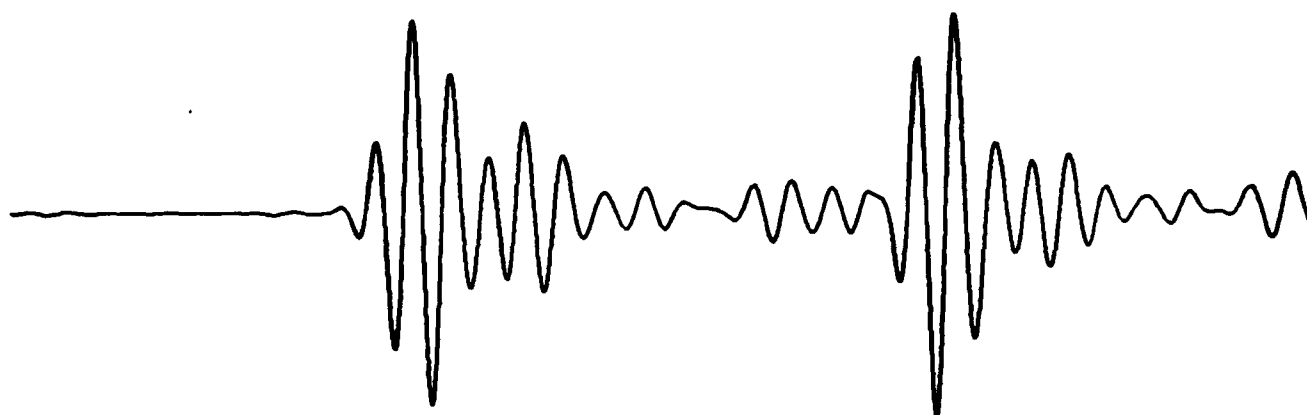


Figure 2. The average spectrum plus or minus one standard deviation of 52 samples of background noise over 18 months from the Wake bottom hydrophones is labelled "A". Also shown are some published noise curves for both ocean-bottom ("B", "C", and "D") and continental ("E", "F", and "G") environments which have been converted from an assortment of units to the scale shown. "B" is a hypothetical "sample spectrum of deep-sea noise" (Urich, 1975; p. 188). "C" is a vertical seismometer measurement made in the Mariana Basin (Asada and Shimamura, 1976). "D" is a vertical seismometer measurement made at 4.6 km depth between Hawaii and California (Bradner and Dodds, 1964). "E" represents low, average, and high noise levels estimated from curves compiled by Brune and Oliver (1959). "F" is an area bounded by the limits of noise curves measured on vertical seismometers for sixteen locations within the United States and Germany (Frantti et al., 1962). "G" is the noise curve for the Oyer subarray of the Norwegian Seismic Array measured during a period "when most of the North Atlantic Ocean was very quiet" (Bungum et al., 1971).

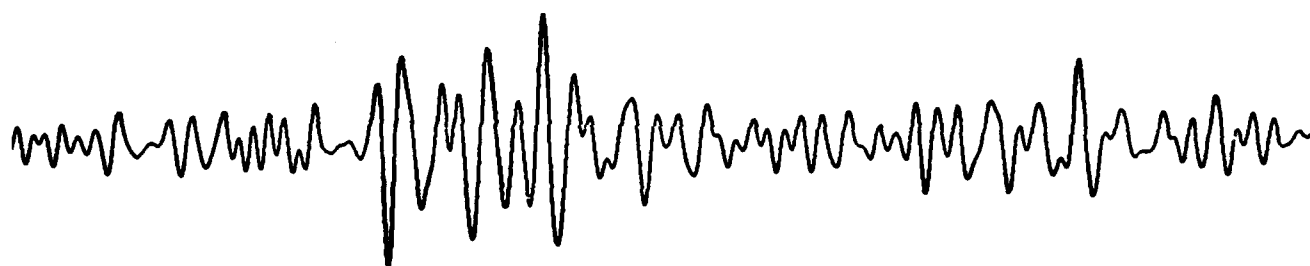


0 5 seconds

Water Wave Multiple



7 JUL 79 EASTERN KAZAKH MB= 5.8  $\Delta=73^\circ$



10 DEC 80 WESTERN SIBERIA MB= 4.6  $\Delta=77^\circ$

Figure 3. Sample time series of P, filtered to maximize signal:noise, from two nuclear explosions recorded on the Wake bottom hydrophones. The upper trace is from a single hydrophone. The lower trace is a composite of signals from two hydrophones, combining the initial pulses and their water wave multiples first, and then summing the two resultant signals. Signal:noise was nearly doubled (the theoretical maximum) by this method.

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